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Orthogonal wavelet decomposition of turbulent structures behind a vehicle external mirror

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ABSTRACT

The turbulent structures of various scales around an externally mounted vehicle mirror have been experimentally investigated. The high-speed PIV technique was first used to measure the instantaneous velocity fields of the mirror wake at a Reynolds number of 7900 in the (x, y)-, (x, z)- and (y, z)-plane. The distribution of instantaneous streamlines and vorticity, time-averaged streamlines and Reynolds stresses were examined. Then the instantaneous turbulent structures were decomposed into the large-, intermediate- and relatively small-scale structures by the wavelet multi-resolution technique. It is found that the large-scale vortical structure shed from the root and side portion of mirror forms the separation region, the intermediate- and relatively small-scale structures are respectively generated from the tip of the mirror and the edge of the mirror. The relatively small-scale structures exhibit the strongest vorticity concentration. It is also indicated that the large-scale turbulent structure makes the largest contribution to the Reynolds stress in the range of separation shear layer behind the separation region. The relatively small-scale structure, however, makes a more contribution to the Reynolds stress in the shear layer near the mirror.

1. Introduction

Since aerodynamic drag reduction is closely related to energy saving, during the last few decades, modern vehicles are characterized by streamlined forms and there are few flow separations from the vehicle surfaces due to the effects of the vehicle manufacturers. However, various bluff shapes that are added to the vehicle body, such as door mirrors, roofracks and front pillar, exhibit aerodynamically generated drag, noise and vibration. Therefore, the extensive effective analysis and control of flow around these external bluff bodies has been becoming a greater concern and an important theme. The aerodynamic noise and vibration caused by the vehicle door mirror has been much studied [1], largely by numerical simulation [2]. The aerodynamic noise and vibration are strongly associated with the flow structures, and the unsteady behavior of the vortex causes the wind noise. But little attention has been paid to the analysis of the complex three-dimensional turbulent structures of the mirror wake from the measured data. Recently the aero-acoustic characteristics of a vehicle door mirror were also studied by numerical simulation as well as experimental measurement [3]. Rinoshika et al. [4] experimentally investigated the flow structure around externally mounted vehicle mirror by the smoke-wire visualization technique and PIV technique. It is found that the length scales of separation region are generally insensitive to Reynolds number, and the size of vortices and the vorticity concentration increase with Reynolds number. To give further understanding of aerodynamic contribution to drag, noise and vibration, the detailed information on three-dimensional as well as multi-scale turbulent structures of mirror wake should be experimentally acquired, which it is important to design the shape of mirror having lower dynamic drag and noise. This is of fundamental significance and has not been previously investigated, thus motivating the present work.

As one of important multi-scale analysis tool, the orthogonal wavelet transform has been widely used to analyze turbulent structures since Yamada and Ohkitani [5] and Meneveau [6] have previously decomposed the experimental data of turbulent structures into a number of subsets based on different scales for statistical analysis. As an application in numerical simulation, Farge et al. [7,8] developed a coherent vortex simulation method decomposing the turbulent structures into coherent and incoherent structures based on orthogonal wavelets. In the area of experimental study, Mouri et al. [9] employed orthogonal wavelet transform to analyze a measured velocity signal of isotropic turbulence and computed statistical measures including flatness factors and scale correlation. To detect the spatial structures of various scales in unsteady flows, Li et al. [10,11] applied wavelet multi-resolution

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technique to analyzing the stereoscopic PIV measurement results and to visualizing the multi-scale turbulent structures from the turbulent images. Recently Rinoshika and Zhou [12–14] have applied the orthogonal wavelet multi-resolution technique to the analysis of the turbulent wakes. This technique is further potentially capable of separating and quantitatively characterizing, other than coherent and incoherent structures in a flow field, the turbulent structures of various scales.

This work aims to apply the orthogonal wavelet multi-resolution technique to decompose the complex turbulent structures of the mirror wake into multi-scale structures at lower Reynolds number and provides both quantitative and qualitative information on these structures for designing the mirror with lower dynamic drag and noise. The high-speed PIV technique was first used to measure the instantaneous velocity fields of the mirror wake. Then the instantaneous turbulent structures are decomposed into the multi-scale structures by the wavelet multi-resolution technique, and the contribution from the turbulence structures of different scales to the Reynolds stresses are quantified.

2. Experimental details

In this study, a 1/3-scaled generic door mirror model (TOYOTA MARK II series), as shown in Fig. 1, is adopted and fixed on a flat plate. For simplifying the complex flows around the door mirror model, the flat plate is assumed to be the car body and the effect of the A-Pillar, etc. is neglected. The height of the mirror model is defined as characteristic length with $L = 45$ mm. The high-speed PIV measurements were conducted in the circulating water channel with a 400 mm × 200 mm working section and 2.2 m long, and Fig. 2 shows the experimental arrangement. Measurements were carried out in three planes: the (x, y)-plane (side view), the (x, z)-plane (plane view) and the (y, z)-plane (rear view); and a constant free-stream velocity of $U_0 = 0.2$ m/s, which corresponds to Reynolds number Re $(\equiv U_0 L \nu) = 7900$. The turbulence intensity was less than 0.5% of the free-stream velocity.

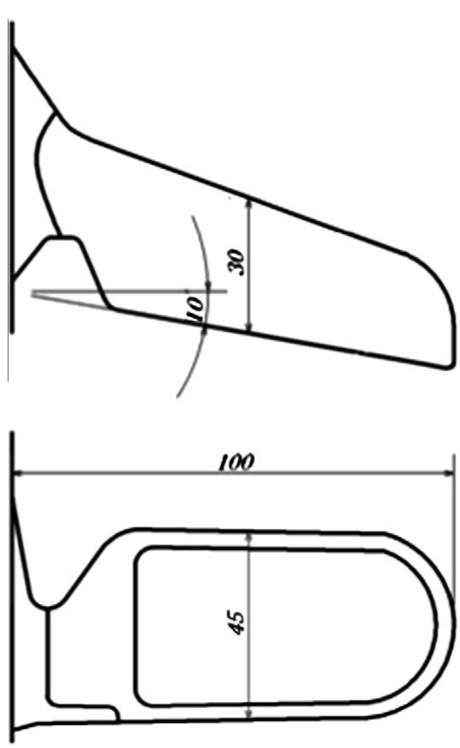

Fig. 1. Door mirror model.

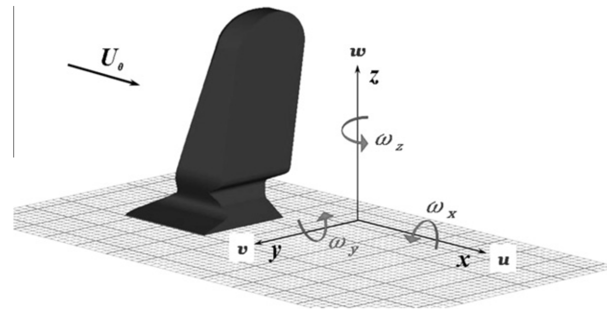

Fig. 2. Schematics of experiment.

A narrow sheet of light produced by a high-intensity continuous light source was used to illuminate the objective flow fields. Polystyrene particles with a diameter of 63–150 μm were seeded in the flow loop as PIV tracers. A high-speed camera (Photron FASTCAM-MAX I2) was used to capture the digital images at a frame rate of 250 fps (frame per second) with a resolution of 1024 × 1024 pixels and the shutter speed of each frame was set at 1 ms. 2000 digital images were analyzed by ProVision PIV software.

3. Orthogonal wavelet decomposition technique

It is a well-known fact that the orthogonal discrete wavelet transform produces the wavelet coefficients that capture local features of the transformed data in both time and frequency, and the wavelet coefficients are independent of and orthogonal to each other. In this work, the one-dimensional orthogonal discrete wavelet transform is adopted and briefly described below.

An orthogonal wavelet basis matrix with twenty coefficients (c_0, $c_1, c_2, \ldots, c_{19}$),

$$C^N = \begin{pmatrix} c_0 & c_1 & c_2 & c_3 & \cdots & c_{18} & c_{19} & 0 & 0 \\ c_{19} & -c_{18} & c_{17} & -c_{16} & \cdots & c_1 & -c_0 & 0 & 0 \\ 0 & 0 & c_0 & c_1 & \cdots & c_{16} & c_{17} & c_{18} & c_{19} \\ 0 & 0 & c_{19} & -c_{18} & \cdots & c_3 & -c_2 & c_1 & -c_0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_2 & c_3 & c_4 & c_5 & \cdots & 0 & 0 & c_0 & c_1 \\ c_{17} & -c_{16} & c_{15} & -c_{14} & \cdots & 0 & 0 & c_{19} & -c_{18} \end{pmatrix}, \quad (1)$$

called the Daubechies wavelet basis with an order of 20, is used, since a higher order wavelet basis has good frequency localization and is relatively smooth. Mouri et al. [9] examined several orthogonal wavelets (Daubechies, Meyer, Harmonic and LMB) and pointed out that turbulent statistics were essentially independent of the choice of the wavelets.

For a one-dimensional data matrix $X^N = [x_1 \quad x_2 \quad \cdots \quad x_{2^N}]^T$, the first orthogonal transform is performed by the product of two matrices:

$$X_w = C^N \times X^N = \left[s_1 \quad d_1^N \quad s_2 \quad d_2^N \quad \cdots \quad s_{2^{N-1}-1} \quad d_{2^{N-1}-1}^N \quad s_{2^{N-1}} \quad d_{2^{N-1}}^N \right]^T \quad (2)$$

where the superscript T denotes a transposed matrix. As evident in the structure of the matrix $\boldsymbol{C^N}$, two convolution operations are carried out. The odd rows of matrix perform an ordinary convolution with coefficients c_0, c_1, $c_2, \ldots,$ c_{18} and c_{19} acting as a low-pass (smoothing) filter, while the even rows perform a different convolution with coefficients $c_{19}, -c_{18}, c_{17}, \ldots, c_1$ and $-c_0$ acting as a high-pass (difference) filter. The resulting first transform coefficient ma-