Three-dimensional Wavelet Multi-resolution Analysis of Flow Structures behind a Vehicle External Mirror

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1. Introduction

The aerodynamic noise and vibration caused by the vehicle door mirror has been much studied [1], largely by numerical simulation [2]. It is evident that the aerodynamic noise and vibration are strongly associated with the flow structures, and the unsteady behavior of the vortex causes the wind noise. 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 high-speed 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. Rinoshika and Watanabe [5] also applied one-dimensional wavelet multi-resolution technique to decompose Reynolds stress measured by high-speed PIV into various scales and analyzed the multi-scale flow structures behind a vehicle external mirror. But little attention has been paid to the analysis of the complex three-dimensional turbulent structures of various scales in the mirror wake from either the numerical or measurement data. 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 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.

This work aims to apply the three-dimensional orthogonal wavelet multi-resolution technique to decompose the complex turbulent structures of the mirror wake into multi-scale structures based on the large eddy simulation and to provide both quantitative and qualitative information on the three-dimensional flow structures of various scales for designing the mirror with lower dynamic drag and noise.

2. Numerical Simulation Conditions

In this study, a 1/3-scaled generic door mirror model (TOYOTA MARK II series) is adopted and fixed on a flat plate. The height of the mirror model is defined as characteristic length with L = 100 mm, and the computational domain is shown in Fig.1. The mesh of hybrid volume (tetrahedra, prisms and pyramids), containing approximately 542,945 cells, is generated in the computational domain. The instantaneous velocity and pressure fields are simulated by LES at a constant free-stream velocity of 15 m/s, which corresponds to Reynolds number Re ($\equiv UL/\nu$) $=10^5$.

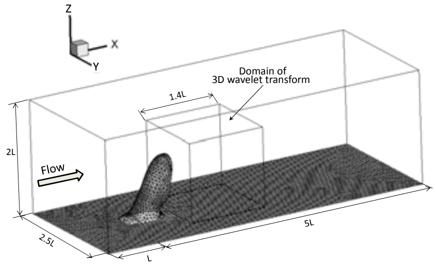

Fig.1 Computational domain

3. 3-D Orthogonal Wavelet Transform

Given a three-dimensional data matrix $V^N = [v_{i,j,k}]$ (i=1,…,2^N; j=1,…,2^N; k=1,…,2^N) having size of $2^N \times 2^N \times 2^N$, its coefficients of three-dimensional wavelet transform $\boldsymbol{S}$ can be obtained by

$$\boldsymbol{S} = \left(\boldsymbol{W} \left(\boldsymbol{W} \left(\boldsymbol{W} \boldsymbol{V}^N \right)^{\boldsymbol{T}} \right)^{\boldsymbol{T}} \right)^{\boldsymbol{T}} \tag{1}$$

where $\boldsymbol{W}$ is constructed based on a cascade algorithm of the wavelet basis matrix and the permuting matrix for all level transform and satisfies $\boldsymbol{W}^{\boldsymbol{T}}\boldsymbol{W} = \boldsymbol{I}$, where $\boldsymbol{I}$ is a unit matrix. This condition enables the three-dimensional discrete wavelet transform to be an orthogonal linear operator and invertible. The inverse orthogonal discrete wavelet transform can be simply performed by reversing the procedure, starting with the lowest level of the hierarchy, that is,

$$\boldsymbol{V}^N = \boldsymbol{W}^{\boldsymbol{T}}\boldsymbol{W}^{\boldsymbol{T}}\boldsymbol{S}^{\boldsymbol{T}}\boldsymbol{W} \tag{2}$$

In order to obtain the wavelet level components of the transformed data, similarity to one- and two-dimensional wavelet multi-resolution analysis [6], [7], the orthogonal wavelet coefficient matrix $\boldsymbol{S}$ is first decomposed into the sum of all levels:

$$S = D_1^N + D_2^N + \cdots D_i^N + \cdots + D_{N-2}^N \tag{3}$$

where D_i^N consists of a wavelet coefficient matrix of level i and a zero matrix, having size of $2^N \times 2^N \times 2^N$.

The inverse orthogonal wavelet transform is then applied to the coefficient of each level, viz.

$$V^N = W^T W^T D_1^T W + W^T W^T D_2^T W + \cdots W^T W^T D_i^T W + \cdots + W^T W^T D_{N-2}^T W \tag{4}$$

where the first term $W^T W^T D_1^T W$ and the last term $W^T W^T D_{N-2}^T W$ represent the data components at wavelet level 1 (the highest grouped frequency) and level N-2 (the lowest grouped frequency), respectively. This decomposition method is referred to as the *three-dimensional wavelet multi-resolution technique*.

4. Results and Discussion

Figure 2 shows the representative instantaneous streamlines and corresponding vorticity contours in the (x, z)- and (x, y)-plane. Here the white and black represent positive and negative maximum values of vorticity, respectively. The streamlines and vorticity contours display the quasi-periodical large-scale vortices with opposite sense of rotation shed from the mirror in the separating region in both of the (x, z)- and (x, y)-plane. The large-scale structures are very similar to the Karman vortices of a cylinder wake. The largest vorticity concentration appears in the shear layer, which is originated from the shear layer instability. This flow structure appears rather similar to the experimental results based on high-speed PIV [4], [5], thus providing a validation of the LES.

Figure 3 displays instantaneous 3D streamlines of the LES, level 2 and 3. Here the color coding represents x-component velocity u_x. Figure 3(b) exhibits the large-scale structure of central scale 62 mm extracted from the LES of Fig.3 (a). A large-scale vertical vortex that is similar to the LES is clearly observed, which also appears in the (x, z)- and (x, y)-plane (Figs.3a and 3b). It forms the flow separation region behind the mirror. At central scale of 29 mm, as shown in Fig.3(c), the several 3D intermediate-scale vortices are observed in or out the large-scale vortex.

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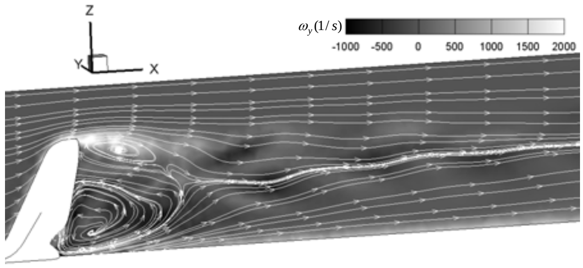
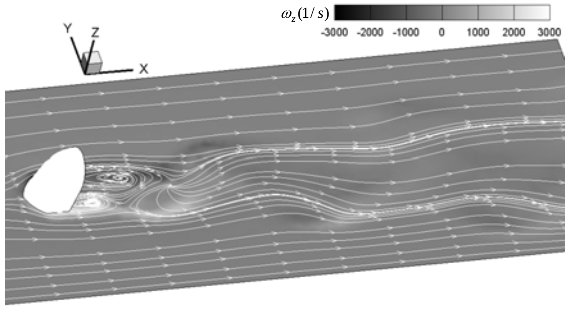
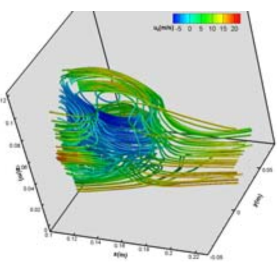


(a) in the (x, z) plane

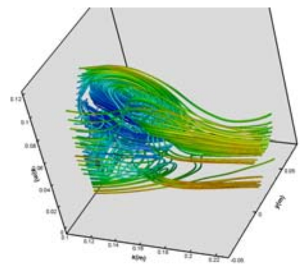


(b) in the (x, y) plane

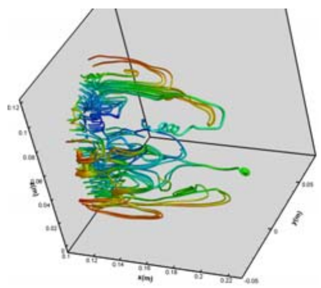
Fig.2 Instantaneous sectional streamlines and corresponding vorticity contours of the LES.



(a) LES



(b) Central scale of 62 mm



(c) Central scale of 29 mm

Fig.3 Instantaneous 3D streamlines of the LES and wavelet components (color-coding indicates x-component velocity u_x)