A Visualization of the Behavior of Noise Source for an Automotive Wind Noise

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Aeroacoustic noise sources under an automotive floor were investigated numerically to obtain the information in order to reduce the sound level of the wind noise. In this preliminary test case, the floor shape of the vehicle was simplified and approximated by the Cartesian mesh model. The computed flow structure was demonstrated by helicity and streamlines, and the distribution of Powell's sound source was visualized by a volume rendering method. Observing the generated MPEG movies, it was found that the vortex structure and shear layer around the front tire influenced the noise source under the floor significantly. From these visualized results, the important information was obtained that the improvement of the shape around the front tire could reduce the wind noise.

Key Words: Aerodynamic Acoustics, Computational Fluid Dynamics, Finite Volume Method, Flow Visualization, Cartesian Mesh, Volume Rendering

1. Introduction

Various noises are generated by a cruising vehicle, for example, suction noise of an engine, exhaust noise, mechanical noise of gears, road noise, tread pattern noise of a tire and aeroacoustic noise. Recently, the aeroacoustic noise of the car becomes comparable to other sources because the noise from the engine room or the power train becomes smaller by measures. As the aeroacoustic noise is proportional to the sixth power of a cruising speed, the intensity of the aeroacoustic sound becomes larger at the high-speed cruising. It is important for passengers to reduce the aeroacoustic noise. From the standpoint of the comfortableness in the vehicle cabin and the regal controls for the noise, in addition, it is important problem to reduce the wind noise.

The aeroacoustic noise of the car can be classified into the internal noise and the external noise for convenience. The internal and the external noise mean the observed sound in the cabin and the outside of the car, respectively. As the internal noise has many transmission paths from the noise sources, it is required that the identification of the noise sources and the transmission function. However, it is very difficult problem to analyze the transmission function for the real vehicles.

Another classification gives the narrowband noise and the broadband noise. For example, an Aeolian tone and a cavity tone that occur at bumps or joints are the narrowband noise. The measures are essential to the narrowband noise because the one appeals to the ear strongly. On the contrary, the broadband noise appears around a front pillar or a door mirror. It is known by many experiments that the peak frequency of 1kHz is observed at the front pillar. The frequency of the wind noise under the floor, also, is ranging from 100Hz to 400Hz (1). In this paper, the broadband noise is considered.

Many researchers have been investigated the sound pressure emitted from an object that has simple shape such as a cylinder. At the far field from the object, the sound pressure is predicted by
Lighthill’s acoustic analogy (2). For the automotive applications, the emitted wind noises from the front pillar or the door mirror are studied using this evaluation method (3, 4). As other expressions of the sound source, Powell’s sound source is proposed in connection with vorticity (5, 6). This Powell’s sound source is related to the motion of the vorticity, there is an advantage of understanding the relation between the structure of the flow and the noise source. Both Lighthill’s and Powell’s theory are based on the assumption of the compactness of the source term. Therefore, these methods cannot use to an entire vehicle body unfortunately because the compactness of the sound source is out of application. However, Powell’s theory is very interesting and it will give us intuitive information to reduce the noise from the viewpoint of the relation between the flow structure and the noise source.

This paper reports the visualization of the noise source and the flow structure under the vehicle floor using Powell’s theory. The flow structure and the distribution of the noise source, in addition, are visualized by a volume rendering method. Furthermore, the behaviors of them are observed by MPEG movies.

2. Numerical Schemes and Visualization Method

In this section, a numerical method is described. The Mach number is about 0.1 for the flow around a running vehicle even with 120 km/h. So the flow is assumed an incompressible flow. The governing equations are the unsteady three-dimensional Navier-Stokes equations and the continuity equation. These equations are discretized by finite-volume method on a Cartesian mesh with conventional staggered variable arrangement. A fractional step method is used to solve the NS equations. For high Reynolds number flow, the convective terms are discretized by QUICK scheme, which has the second-ordered accuracy in the space. Unsteady terms are approximated by Euler explicit scheme. Although higher-ordered time integration scheme should be required for the detailed investigations such as frequency analysis, the first-ordered scheme is used for this computation. The first-ordered scheme seems to be not fatal because the aim of this study is qualitative discussion based on the flow structure larger than the mesh scale.

Next, boundary conditions are discussed (7). A uniform flow condition with the velocity \( U_0 = 30 \text{(m/s)} \) is imposed on the inlet of the computational domain. A moving ground with the running car is assumed on the ground condition but the tire is not rotate. A no-slip condition for the velocity and a Neumann condition for the pressure are used for the all surfaces of solid walls.

The flow was computed on an NEC SX5 with 2CPUs at RIKEN. It took about 10 hours (Elapsed time) including the visualization time for the calculation of 14000 steps.

In the low Mach number flow, there are three well-known expression of the sound source, namely by, Lighthill, Powell and Ribner (8). Among them, Powell’s source was chosen to visualize by the sound source related to the flow structure. The frequency range to be considered is ranging form 100Hz to 400Hz. Taking account of the relation in the low Mach number flow that a wavelength of the sound is proportional to a reciprocal of the Mach number, the corresponding vortex scale to those frequencies is ranging from 0.085m to 0.3m. For this reason, the mesh size was decided to be 0.02m to capture those vortices. The shape of the computational model is simplified as shown in Fig. 1.

The flow was visualized by a volume rendering function to recognize the whole flow field intuitively which is include in an RVSLIB provided by NEC (9, 10). The RVSLIB is one of the visualization libraries and called from a source program directory. Therefore, the flow computation and the visualization performed simultaneously.

3. Visualization Results

Firstly, Fig. 2 shows the flow under the floor by means of helicity, which is defined by:

\[
h = \omega \cdot v = \text{curl}(v) \cdot v
\]  

(1)

The color appears in Fig. 3 indicates a sign of the vorticity, that is, red and blue correspond to a right-handed rotation of the vortex and a left-handed rotation, respectively. In addition, the brightness shows the intensity of the helicity. This helicity distribution shows that the large helicity regions are found at the corner of a front undercover and the outside
of the front tires. Between both the front tires, the helicity regions have the opposite sign are stretched from each tire and interfere at the center. A similar structure is found around the rear tires. Besides, many vortex tubes are found under the front undercover. Observing the behavior of the helicity distribution by MPEG movies, the vortex tubes around the tires are frequently shaking. On the other hand, the vortex tubes are little shaking at the corner of the front undercover.

Secondly, Fig. 3 shows the distribution of Powell’s sound source term (2).

\[ \frac{1}{c_s^2} p_x - \nabla^2 p = \rho_s \text{div}(\omega \times v) \]  

(2)

It is found that the strong noise sources exist around the tires and the center of the floor. To take the distribution of the helicity into account, the strong sound source appears where the helicity fluctuate significantly in time. This is obvious from the definition of Powell’s sound source.

Next, the flow field around the front tire is visualized by the streamlines. Fig. 4 shows several vortex structures, such as the stretched vortex outside the tire, turbulent wake and the flow towards to the center. Observing from another direction (Fig. 4(b)), there is a vortex structure like a horseshoe vortex. Moreover, the streamline from the tire toward the center is just above on the ground. The vortex around the tire seems to have the same basic structure as shown in Fig. 5, which shows the characteristic of the flow around the cube mounted on a flat plate. It is considered that the structure of the horse-shoe vortex is deformed by the existence of the floor. It is easy to guess that the strong sound source is generated on the ground by the shear layer of the horseshoe vortex.

Up to here, we have pointed out that the flow around the tire generates the dominant sound source using the visualization of both the flow structure and the noise source. This assumption leads the possibility to reduce the wind noise by the optimization of the flow.

4. Concluding Remarks

So far, we have described a flow around a vehicle by a Cartesian mesh method and visualized the flow structure under a floor by a helicity distribution. In addition, the noise source was calculated by using Powell’s theory. The unsteady behavior of the helicity and Powell’s noise source indicated that the vortex structure around the tire played important role for the noise source under the floor. In concluding, we should note that if the shape will change around the front tires, the noise under the floor would be reduced.

References

Fig. 1 Voxel model for the flow computation. (Toal voxel is 128x384x128 and 20mm in size)

Fig. 2 Instantaneous helicity distribution of the space under the floor (Bottom view; left side is upwind direction).

Fig. 3 Instantaneous distribution of Powell’s noise source term $\nabla \cdot (\mathbf{u} \otimes \mathbf{u})$. Range is from -6000 to +6000.

Fig. 4 Stremlines around the front tire.

Fig. 5 A flow around a cube on a flat plate. A horsehoe vortex is visualized by the volume rendering method.