An Efficient Method for Prediction of the Flow-induced Vehicle Interior Noise

Yingjie Liu¹, Wenbo Lu² *, Qi Zhang², Xing Wang², Xiang Yin³, Hangsheng Hou¹

¹Authors are with the China Faw Group Co. Ltd, State Key Laboratory of Comprehensive Technology on Automobile Vibration and Noise & Safety control, Changchun, China
²Authors are with the Shanghai Hikey-Sheenray Information Technology Co., Ltd., Shanghai, China.
³Author is with the School of automotive engineering, Wuhan University of Technology, Wuhan, China

*Corresponding author: wenbo326@163.com

Abstract. Wind noise is an important attribute for vehicle interior quietness. To improve the efficiency of wind noise simulation, a method of Stochastic Noise Generation and Radiation (SNGR) is used to rebuild the flow field based on steady simulation result. For wind noise simulation, the flow field result of transient simulation is only applied to low frequency, and the result of the SNGR method is applied to middle and high frequency. Finally, correcting the SNGR result by correction coefficient and combining the two results. The experiment and simulation results have good agreement. The results shows that the hybrid method for predicting the wind noise in vehicle can not only obtain good results, but also improve computational efficiency.

1. Introduction

With the improvement of people's consumption level and concept, the performance of NVH has gradually become one of the hot point of consumers' attention. When a car is travelling at high speeds, wind noise generated by the A-pillar and side mirror is one of the main sources to the interior noise level [1, 2]. In the process of vehicle development, due to the high cost of wind tunnel measurements, numerical simulations have become an important method to investigate vehicle wind noise. Traditionally, the flow field result was obtained by the transient CFD simulation, then the result is used to calculate interior wind noise by finite element method (FEM) or statistical energy analysis (SEA). For example, Brenner P.G. et al. [3] and Kurosawa Y. [4] combined transient CFD simulation and SEA to predict interior wind noise of vehicle, while Schell A. et al. [5], Cho M. et al. [6] and Wang Y.S. et al. [7] combined transient CFD simulation and FEM to predict interior wind noise. All of them have got good results, and it proved the feasibility of CFD/SEA and CFD/FEM method.

However, the computational cost for the transient CFD simulation is quite high, and it is also not easy to convergence. For this reason, a new kind of method: SNGR (Stochastic Noise Generation and Radiation) can be applied. The SNGR method reconstructs the turbulent region based on steady flow field. Compared with transient CFD simulation, the SNGR method based on steady results can greatly reduce the time required for CFD simulation.
In previous researches, the SNGR method has been studied and applied by some scholars. For instance, Yu P. et al. [8] used this method to study the slat noise. The results show that this method can effectively predict the distribution characteristics and intensity of the slat noise. M. Mesbah et al. [9] used this method to analyze the two-dimensional axisymmetric subsonic jet, and explored the effect of the sound source area size, turbulence integral length, and random series on the result of this method. Guan P. et al. [10] used this method to analyze the acoustic noise in the rearview mirror area of a vehicle model. The results show that the method can greatly reduce the demand for computing resources and qualitatively analyze the sound field results in the mid-to-high frequency. But unfortunately, there are no experimental results in their study for comparison.

When studying the wind noise of the simple rearview mirror model, Felix et al. [11] obtained the flow field results using SNGR and transient CFD simulation methods respectively. When comparing the acoustic calculation results with the experimental values, they found that the acoustic result calculated using the data of transient CFD simulation is in good agreement with the experimental values, but there is some error between the acoustic results calculated by the data of SNGR method and the experimental value. Therefore, they proposed that the acoustic result calculated by data of SNGR method should be corrected by the result calculated by data of transient CFD simulation, and a correction formula was given.

However, there is a disadvantage of SNGR method that it is not accurate in low frequency. For this reason, in this paper, we combine the data of transient CFD simulation and SNGR method to predict the interior wind noise of a real car. Specifically, the acoustic result in low frequency is calculated by the data of transient CFD simulation, and the result in middle and high frequency is calculated by the data of SNGR method. Because SNGR method is not accurate in low frequency, the next step is corrected the result of SNGR method by the result of transient CFD simulation, and the correction formula given by Felix et al. [11] is applied. Finally, combining with the two results after correction, we can get the acoustic result of the whole frequency. For the reason that transient CFD simulation only used for low frequency and the SNGR method just requires state flow field results, less computational resource is used in the whole solving process.

2. Basic Theory

2.1. SNGR method

The SNGR method relies on the assumption that the incompressible turbulent velocity field can be decomposed into its Fourier modes [12, 13]:

\[
U'(x,t) = 2 \sum_{n=1}^{\infty} u_n \cos[k_n(x - \text{i}U_c t) + \phi_n + \omega_n t] \sigma_n
\]  

(1)

where \( u_n \), \( \phi_n \) and \( \sigma_n \) represent the amplitude, phase and orientation of the \( n \)-th mode in the wave number space respectively. \( k_n \) is the turbulent wave number, and \( \omega_n \) is the angular frequency of the \( n \)-th mode. \( U_c \) is the local convective velocity. The amplitude \( u_n \) is calculated by:

\[
u_n = \sqrt{E(k_n) \Delta k_n}
\]  

(2)

where \( E(k_n) \) is von Karman-Pao semi-empirical spectrum.

2.2. Acoustic analogy theory

The classical acoustic analogy theory was put forward by Lighthill in his paper. The solution of Lighthill acoustic analogy equation is the integral solution of green's function, but for complex boundary, green's function is often difficult to obtain. Oberai et al. [14] proposed a new method to solve the acoustic analogy equation. After obtaining the variation form of Lighthill acoustic analogy equation in frequency domain, the finite element method is used to solve the equation.
We define the solid area $\Omega_s$ is surrounded by air flow, $\Gamma_s$ is the edge of the solid area. $\Omega_f$ is the turbulent region. Due to Navier-Stokes equation, the fluid can be regarded as uniform in the region of the $\Omega_s$ and $\Omega_\infty$. In addition, $\Gamma_f$ is turbulent region (source area) of the outer boundary, $\Gamma_a$ is acoustic truncation.

By Oberai et al., a variational formula for solving aeroacoustic problems can be obtained:

$$
\left(\nabla w, \nabla \rho'\right)_{\Omega_s} - k^2 \left( w, \rho' \right)_{\Omega_s} - \left( w, \rho'' \right)_{\Gamma_f} = -M^2 \left( \nabla w, \nabla T \right)_{\Omega_s}
$$

(3)

where $\rho'=\rho-1$, $\rho$ is fluid density, $k=\omega M$, $\omega=2\pi vL/V_0$, $M$ is Mach number, $v$ is frequency, $w$ is a weighting function, $T$ is the Fourier component of the turbulent tensor at frequency $\omega$. For a scalar $v$, $v_n$ represents the normal component of its gradient, that is, $v_n=\nabla v \cdot n$. For any two vectors $w(x)$ and $u(x)$ ($x \in \Omega$), define:

$$
\left( w, u \right)_{\Omega_s} = \int_{\Omega_s} \overline{w} \cdot u \, d\Omega
$$

(4)

where $\overline{w}$ is the complex-conjugate of $w$.

3. Experiment
The physical model, Hongqi H7, was tested at the Shanghai Ground Vehicle Wind Tunnel Center (SGVWTC). The wind tunnel at SGVWTC is an acoustic wind tunnel. The test vehicle is installed at the test section (See Fig. 2). The air-inlet grille and body gaps were sealed with tape, and chassis and wheels were partially closed. Five microphones were installed on the surface of the left window to measure the fluctuation pressure.

![Fig 1. Test vehicle and microphones position.](image-url)
As shown in Fig. 4, four dummy heads were installed in the driver's seat, the front passenger seat, and the rear seats.

![Mannequins in car.](image)

The test vehicle is in the state of 0 yaw angle and the incoming wind speed is 120km/h. When the flow field around the test vehicle reaches a stable state, the microphones start to collect data. The sampling time is 10s, and the time step is $2.08 \times 10^{-5}$s.

4. Numerical Simulation for Exterior Flow

4.1. Model

A computational fluid dynamic (CFD) domain, the same as the real wind tunnel dimensions was constructed, as shown in. The length, width and height are 23m, 18m and 13m respectively. The distance between the velocity inlet and the vehicle model is 2m. In addition, the settings of boundary condition for the computational domain are listed in TABLE I.
Fig 3. Calculation domain.

Table 1. Boundary condition.

| Boundary of the computational domain | Setting                        |
|------------------------------------|--------------------------------|
| Inlet                              | Velocity inlet, 140km/h        |
| Outlet                             | Pressure outlet, 0Pa           |
| Model and Ground                   | No-slip wall                   |
| Other boundaries                   | Slip wall                      |

The surface grid size on the car is set to 2-10mm, the maximum size of volume grid in the sound source field is set to 4mm, and the maximum size of the volume grid close to the rear-view mirror, pillar A and door handle is 1mm, suitable for the capture of turbulent structures exhibiting frequencies at least up to 3000Hz. For LES, the Y+ value on the surface of the sound source areas should be about 1. Therefore, a 5-layer boundary layer grid is set on the surface of the car, and the thickness of the first layer is 0.02mm, and the total thickness is 2mm. Finally, the total grid number is about 0.15 billion, and the surface grid is shown in Fig. 4.

To validate the accurateness of numerical simulation, the pressure monitoring points whose positions are the same as the microphones in the experiment were set up in the left window to obtain the turbulence pressure fluctuation.

Fig 4. The surface grid of car.

STAR-CCM+ was used to solve the flow field. In order to make the transient solution easier to converge, the steady-state solution was first applied to the flow field, and the k-ε model was used for steady-state solution. After the steady-state solution converges, the flow field result obtained from the steady-state solution was taken as the initial field of the transient solution, and LES model was used for transient solution. The calculation frequency is 100-2500Hz. The transition flow field computation is set with time step of $2 \times 10^{-5}$s, sampling time of 0.1 s.
4.2. Result
The benchmarking requirements for simulation and experiment results of monitoring points are as follows: the trend of the simulation and test should be consistent within 100-2500Hz, and the error of OFPL (overall fluctuation pressure level) should be less than or equal to 3dB(A). The 1/3 octave results of monitoring points are plotted in Fig. 10. It shows that the computational results had a good agreement with the experiment results, and the OFPL errors are all within 3dB(A), which meets the engineering requirements. The results of the flow field model are then used for acoustic calculation.

![Graph 1](image1.png)

**Fig 5.** Comparison of simulation and experiment.

5. Interior Wind Noise Calculation

5.1. Model
The finite element method and infinite element method are used to establish the acoustic propagation models of the external field and internal field, respectively. The acoustic computational grid needs to meet the requirements that one wavelength should include six nodes at least, therefore, the maximum grid size of the acoustic simulation model is set as 18mm.

As shown in Fig. 6, the acoustic model of the external field is divided into the source region, buffer region and infinite element boundary. The flow field data of transient CFD simulation and SNGR method will be converted to the sound source in the source region by Lighthill acoustic analogy, and the
converted results will be mapped to the window surface by integral interpolation method. The function of the infinite element boundary is to simulate the non-reflection boundary. The buffer region is set between the sound source area and the infinite element boundary.

The acoustic model of the internal sound field is shown in Fig. 7. The model includes seats, dummies, steering wheels, window glass, and other structures. Two monitoring points were set up near the driver's ears. The main part of the model is the inner air field grids and the window glass grids. The former is used for the calculation of acoustic propagation inside the cabin, and the latter is used for the loading of sound sources. Otherwise, the shield window is different from other windows because of its PVB (polyvinyl butyral) interlayer, and all parameters of glass and PVB are listed in TABLE II and TABLE III. In addition, it is necessary to consider the attenuation of the sound when it propagates in the internal cavity. Since the materials of cavity are complex, we consider the sound absorption boundary by adding an imaginary part to the sound velocity, which is calculated based on the reverberation time.

### Table 2. Glass parameters.

| Parameter               | Value |
|-------------------------|-------|
| Young's modulus (GPa)   | 70.2  |
| Poisson's ratio         | 0.23  |
| Density (kg/m³)         | 2500  |
| Thickness (mm)          | 5     |
Table 3. Pvb parameters.

| Parameter                     | Value  |
|-------------------------------|--------|
| Young’s modulus (MPa, 23°C)   | 1.4    |
| Poisson’s ratio               | 0.47   |
| Density (g/cm³)               | 1.07   |
| Thickness (mm)                | 0.76   |

5.2. Result based on transient CFD simulation

All wind noise results in this paper were calculated by ACTRAN. The SPL results of driver’s ear in 100-1500Hz are calculated by the data of transient CFD simulation, and the spectrums are plotted in Fig. 8. The trend of experimental and simulation curves is basically the same, and the deviation can be acceptable. Because the interior cavity of the real vehicle is more complex than the simulation model, it is inevitable to have some errors between the simulation and experiment. It can be considered that the acoustic analogy calculation method can accurately predict the wind noise inside the vehicle.

Fig 8. Result of transient CFD simulation.
5.3. Result based on SNGR method

Based on the data of steady-state CFD simulation calculated by the SNGR method, the SPL results of driver’s ear in 100-3000Hz are obtained, and the spectrums are plotted in Fig. 9. It shows that the results below 1000Hz have a large error compared with the experiment. However, the trend of SPL slowly decreasing in the 1000-3000Hz can be successfully captured by simulation. Compared with the experiment, there are two problems in the simulation results: first, the simulation results of the driver's ear have a rising trend in the range of 2000-2500Hz, and then a sudden decline after 2500Hz, which is inconsistent with the trend of the experiment. Second, the OSPL (overall sound pressure level) of the simulation results is about 20-25db (A) smaller than the experimental results.

![Fig 9. Result of SNGR method.](image)

5.4. Combining of the two simulation results

In Felix et al.’s research [11], they compared the results of interior wind noise based on the transient CFD simulation and SNGR method when calculating the wind noise caused by the rearview mirror. Then a conclusion was put forward that the calculation result based on the SNGR method should be corrected by the results based on the transient CFD simulation, and they also gave the following correction formula:
\[ L' = 20 \log\left(\frac{\alpha p}{p_0}\right) \quad (5) \]

where \( L' \) is the sound pressure level after correction, \( \alpha \) is the correction coefficient, and its value is obtained after the result is corrected, \( p \) is the sound pressure before correction, and \( p_0 \) is the reference sound pressure.

In this calculation, the result based on the SNGR method was corrected by the result based on transient CFD simulation in the range of 1000-1500Hz, and the equation 12 was used for the correction process. The comparison before and after correction is shown in Fig. 10.

In the process of correction, the correction coefficient of the model is determined as \( \alpha = 16 \). After the correction is completed, the two results are combined in the range of 100-3000Hz, then compared with the experimental results (see Fig. 11). The figure revealed that the curves of simulation result agree well with the experiment ones. Therefore, if the interior wind noise should be predicted after reshaping review mirror or A pillar, we can use the data of transient CFD simulation to predict it only in low frequency, while the result in middle and high frequency can be predict by the data of SNGR method, then use the correction coefficient calculated before to combine the two result. Since only transient calculations are needed in the low frequency band, compared with the use of transient CFD simulation data for full-band wind noise calculation, the method in this paper can save a lot of calculation time and improve efficiency, and can get the results which agree well with experiment value.

Fig 10. The comparison before and after correction.
6. Conclusion
In this paper, the accurate exterior flow field of Hongqi H7 is computed, and the results are in good agreement with the experiment. In the process of predicting the interior wind noise, the data of transient CFD simulation is used in the low frequency and the data of the SNGR method is used in the middle and high frequency. Then, the acoustic results based on the SNGR method are corrected by the results based on transient CFD simulation, and the correction coefficient is obtained. Finally, after combination, the simulation results of interior wind noise in 100-3000Hz are obtained, which are in good agreement with the experimental values. In the above process, we can get an efficient method to predict interior wind noise of vehicle, and this method can be applied in the process of shape optimization of vehicle’s review mirror and A pillar.

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