Numerical simulation of heavy truck’s aerodynamic noise

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Abstract. A 3D numerical simulation is built on heavy truck including cab, frame, and tires. And vehicle exterior flow field in steady state is computed by computational fluid dynamics software. In the computation process, the distribution of sound power levels on the surface of vehicle body as well as the connection between sound power level and vehicle speed are obtained from aerodynamic noise source, which is using broadband noise source models. Taking the steady flow field results as original values, the exterior flow field computations in transient state are performed by large eddy simulation. Based on the transient fluid field, the near field aerodynamic noise from cab accessories is predicted using FW-H model, and the comparison of the simulation results and the test results is carried out. The results show that the aerodynamic noise sources are from the upwind side with a great pressure gradient. Attention should be paid more on rearview mirror, diversion trench and sun visor for Aerodynamic noise optimization of heavy truck. The maximum sound power level of aerodynamic noise in vehicle body accessories is quadratic to vehicle speed. And the aerodynamic noise of heavy trucks is analysed by numerical simulation, in which noise distribution law is consistent with the test. Therefore, the numerical simulation can be adopted to provide the guidance for the design of vehicle body with low noise.

1. Introduction

The noise level of heavy truck is one of important performance parameters. It causes environmental noise pollution and affects driving comfort. At present, it has been an important indicator for measuring the overall quality of vehicle. Vehicle noise is mainly composed of engine noise, transmission noise, tires noise, intake and exhaust noise, plate vibration noise, aerodynamic noise and so on. Significant achievements have been made in reducing engine noise, tire noise, intake and exhaust noise after years of effort by researchers. As speed-increasing and sealing property-improving, aerodynamic noise at high speed has become the crucial part of vehicle noise.

At present, in the terms of passenger vehicle and high-speed train, the aerodynamic noise has been studied widely by specialists and scholars, and remarkable achievements have been made in reducing aerodynamic noise. However, there are few studies on the aerodynamic noise of heavy trucks. The main reasons are that the aerodynamic noise from traditional heavy trucks is relatively less due to its low speed, and most noises are from the power transmission system because of the powerful engines. According the internal and international market situation, the higher the speed of heavy trucks, the greater the proportion of aerodynamic noise. Research shows that, the aerodynamic noise increases with the speed to the sixth power, which means for each double of speed, aerodynamic noise will
increase by about 18 db. As speed is below 60 km/h, it can obviously affect internal vehicle. In 1972, as Boeheim in Germany tested aerodynamic noise on 15 kinds of cars, he found that when vehicle speed reached over 113 km/h, the inside noise generated by aerodynamic noise from exterior flow field was 62-78db (A), and when the speed arrived 177 km/h, the inside noise was up to 72-87db (A). Meanwhile, for the flourishing development of new energy vehicles in recent years, its market share in the future will take higher. As early as 1999, as Norman et al from Ford Motor Company in the United States proposed, although the noise of electric vehicles was less than that of traditional internal-combustion engine vehicles, there were more component noises and wind noises in the absence of engine masking effect. Therefore, the study of aerodynamic noise on heavy trucks is significant.

Tests and simulation are the main methods of aerodynamic noise research. The tests include real vehicle test and acoustic wind tunnel test. Common simulations include numerical computation method that is used to study the noises generated by fluid and solid boundary interaction based on computational aeracoustics (CAA). In 1952, Lighthill put forward the Lighthill equation describing fluid motion and sounds based on Navier-Stokes equations (N-S equations for short) that describes fluid flowing. In 1955, based on the theory of Lighthill, Curle noticed the influence on a stationary solid surface. In 1969, Ffowc Williams-Hawkings deepened the theory of Curle to the noise problem caused by the interaction between the moving wall and the fluid, and then proposed the Ffowc Williams-Hawkings equation (FW-H equation for short).

2. Theory basis

2.1. Proudman equation

There is no obvious frequency band for turbulence in many engineering applications, and acoustic energy is distributed continuously in frequency over a wide band, which is called broadband noise problem. In this problem, Proudman equation is widely used. On the basis of acoustic analogy theory of Lighthill, Proudman ignored the differential of delay time and replaced it to equivalent synchronous covariance, in order to derive a radiated sound power expression of isotropic turbulence per unit volume at lower Mach number and higher Reynolds number. After that, Lilly dealt with the delay time differential and derived a new expression of radiated sound power. Both of these expressions can calculate the radiative sound power $P_A$ (in unit W/m³) of isotropic turbulence per unit volume.

$$P_A = \alpha \rho_0 \left( \frac{u^3}{l} \right) \frac{u^5}{a_0^5}$$

Type (1) can be written in forms of $k$ and $\varepsilon$.

$$P_A = \alpha_k \rho_0 \varepsilon M_t^5$$

Sound power level is defined as

$$L_p = 10\log(P_A/P_r)$$

Type: $u$ is turbulence speed, $l$ is turbulence scale, $a_0$ is sound speed, $\alpha$ is model constant, $M_t = \sqrt{2k/a_0}$. $P_r = 10^{-12}$W/m³ is reference acoustic power.

In the type, $\alpha_k$ takes $\alpha_k = 0.1$ based on isotropic turbulence computation of Sarker and Hussaini. In the calculation, exterior vehicle steady flow field is computed by standard $k-\varepsilon$ turbulence model first to obtain the turbulent kinetic energy and turbulent dissipation rate of each node in the flow field. Then sound power level distribution is got after calculating the noise power at a node of the volume element by Proudman equation.

2.2. Fowcs Williams-Hawkings equation

The noise caused by the running vehicle and air interaction accords with FW-H equation:
\[
\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i} \left[ (p_i \delta_{ij} - \tau_{ij}) \frac{\partial f}{\partial x_j} \right] + \frac{\partial}{\partial t} \left[ \rho_0 u_i \frac{\partial f}{\partial x_i} \delta(f) \right] \tag{4}
\]

Including: \(T_{ij} = (P_{ij} + \rho u_i u_j) - (c_0^2 \rho + p_0) \delta_{ij} = \rho u_i u_j - \tau_{ij} + (p - c_0^2 \rho) \delta_{ij}, \) \(u_i\) means the fluid velocity component in \(x_i\) direction, \(\delta(f)\) for Dirac-delta function, \(\delta_{ij}\) for Kronecker delta.

On right side of equation (4), the first one is Lighthill sound source, which is quadrupole sound source, because \(T_{ij}\) is Lighthill stress tensor that includes velocity variables. The second one is dipole source caused by pressure pulsation. Third one is monopole source caused by surface acceleration.

3. Numerical model

3D geometrical model is built on a heavy truck as research object including cab, frame, axle, tires, etc. As various shapes and sizes of containers can be hung behind the head of motor tractor, only the traction head and chassis are analyzed in this model. The geometric model of vehicle body was divided into triangular grid. For the complex model, using triangular grid can improve mesh quality as well as retain the original geometric features. To perfectly seize aerodynamic noise of vehicle body, there are many detail features retaining including cab doorknob, rearview mirror and so on, which conduct mesh encryption. The final body grid model is shown as figure 1.

![Figure 1. Surface mesh model.](image)

For the vehicle is running on the plat ground, the length, width and height of the computational domain are respectively 34 m, 14 m and 12 m according the vehicle body size. The vehicle head is 6.5 m away from the inlet. The schematic of computational domain and boundary conditions is shown as figure 2. Meanwhile the type of inlet is velocity-inlet. The velocity of inlet is equal to vehicle speed. The outlet is taken as pressure outlet, the ground as wall boundary, the top surface and two sides as
symmetry boundary, and the surface of vehicle body as impenetrable solid wall. Finally, the unstructured tetrahedral grid of global computing domain is generated in accordance with the body surface and each boundary surfaces. The minimum grid size is 2 mm, the maximum grid is 180 mm, and the total grid number is more than ten millions.

4. Surface noise source analysis

4.1. Surface sound power level distribution

It can rapidly assess the noise intensity caused by moving surfaces in fluid by using broadband noise sources model. All source terms only need the typical RANS equation solution, for transient flow solution is unnecessary. Therefore, there is less calculation in broadband noise sources model than that in FW-H equation. Surface sound power level can be obtained using broadband noise sources model. Based on the k-ε two equation turbulence model, the steady exterior flow field of a vehicle at a constant speed on the plat ground is calculated, and the sound power level distribution of vehicle body surface is obtained by using broadband noise model.

When the vehicle speed is 100 km/h, the static pressure, speed and sound power level distribution of body surface is obtained by computation, shown as figure 3. The results show that the sound power level is higher in the location where surface speed and pressure gradient are greater. Regardless of containers, higher sound power level is mainly from the upwind side of rearview mirror, sun shield, diversion trench, bumper, tire and other parts. Considering the effect of aerodynamic noise on driver’s ears, the aerodynamic noises caused by bumper, tire and other places far from door and glass are difficult to be heard. The rearview mirror, sun shield and diversion trench are closer to door and glass gap, so that the noises may easily come into the vehicle from these gaps due to poor sealing. As a result, it influences the parotic noises in the vehicle.

**Figure 3.** Flow field parameter distributions. (a) Static pressure distribution, (b) Velocity distribution and (c) Sound power level distribution.
Figure 4. Sound power level distribution of main parts. (a) Sound power level distribution of right diversion trench, (b) Sound power level distribution of left diversion trench, (c) Sound power level distribution of right mirror, (d) Sound power level distribution of left mirror and (e) Power level distribution of sun shield.
The distribution of sound power level in rearview mirror, diversion trench and sun shield is shown as figure 4. It can be seen that higher sound power level of rearview mirrors is generated at the root of connecting rod, close to the mirror body and edge of door. Higher sound power level of sun shield is generated at the lower edge. Higher sound power level of left and right diversion trenches appears at leading edge of the out plates and fins. All of them are the positions where high static pressure transforms into low static pressure, and low wind speed changes into high wind speed on the upwind side, that is, the location where there is greater static pressure and speed gradient places. Maximum sound power level of each accessory is shown in table 1. Ultimately, the biggest noise comes from rearview mirrors, and the secondary noise is from diversion trenches and sun shield is followed. The asymmetry of left and right accessories as well as errors in simulation result in inconsistent distribution of sound power level at rearview mirrors and diversion trenches.

Table 1. Maximum sound power level of main positions.

| Position             | Maximum Sound Power Level |
|----------------------|---------------------------|
| Left Mirror          | 100.23 dB                 |
| Right Mirror         | 98.36 dB                  |
| Left Diversion Trench| 95.75 dB                  |
| Right Diversion Trench| 87.74 dB                  |
| Sun Shield           | 91.6 dB                   |

4.2. Surface acoustic power at different speeds
When a vehicle is traveling at constant speeds, the maximum sound power level curve of major components is as shown in figure 5. From that, the sound power level of each components sequence in same. The highest is left mirror, following right mirror, left diversion trench, sun shield, right diversion trench. The maximum sound power level of each parts increases with speed improving, and is quadratic to speed.

![Figure 5. Maximum sound power level of each position at various vehicle speeds.](image)

5. Near-field aerodynamic noise analysis
Taking the steady flow field results as original values, the transient flow field computations are performed by large eddy simulation (LES), and FW-H equation is solved at the same time. All vehicle
surfaces are taken as aerodynamic noise sources, and noise receivers are arranged near key positions such as rearview mirrors and sun shield, shown as figure 6. Set time step to 0.00033 s, and sound pressure result of each receiver with the highest frequency of 1500 Hz are computed. To verify the accuracy of simulation results, it is tested on a real vehicle with the same noise receivers, shown as figure 7.

![Figure 6. Sound receivers schematic.](image)

![Figure 7. Microphones layout. (a) Microphones on rearview mirror, (b) Microphones on diversion trench and (c) Microphones on sun shield.](image)
When the vehicle speed is 100 km/h, the simulation and test results comparison for A-weighted sound pressure level is shown as figure 8. It can be seen that test sound pressure level of each receiver is about 20 dB (A), larger than that in simulation. On the one hand, there is the simulation error. On the other hand, there is only aerodynamic sound source in the simulation. While the vehicle is traveling in test, other sound sources, such as power transmission noise and tires noise, contribute more to measurement points, which results in the test results are generally larger than the simulation results. However, the near field sound pressure level of rearview mirrors, diversion trenches and sun shield are in same sequence, which is basically consistent with the sequencing results in steady state simulation. The maximum noise is from connecting rod of left rearview mirror. Therefore, the simulation model can reflect the aerodynamic noise distribution of vehicles, which also can be adopted for qualitative analysis and research of aerodynamic noise, so as to provide reference and guidance for vehicle body design with lower noise.

![Figure 8. Comparison of sound pressure level between test and simulation.](image)

6. Conclusion
- As vehicle is running, the greater aerodynamic noise is from the big pressure gradient at upwind side, that is, the positions where high static pressure changes to low static pressure, and low wind speed changes to high wind speed at the upwind side.
- The greater aerodynamic noises for heavy truck, which has a huge effect on inside vehicle, are mainly the positions of rearview mirrors, diversion trenches and sun shield, needing wind noise optimization. Meanwhile, the rearview mirror generates the largest aerodynamic noise, so it is necessary to focus on the connecting place between the rearview mirror rod and mirror body, as well as its upwind edge.
- The maximum sound power level of each parts increases with speed improving, and is quadratic to speed.
- Based on the analysis of aerodynamic noise of heavy truck with numerical computation method, the distribution rules consistent with tests can be obtained. Therefore, the simulation results can help the optimization of vehicle body accessories and provide the guidance of body design for low noise.

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References
[1] Yang B 2008 Research on automobile exterior aerodynamics noise (ChangChun: JinLin University)
[2] Yu L, Huang H, Shao G T and Lin X Q 2016 Aerodynamic optimization analysis of the heavy
duty truck based on PowerFLOW Auto Sci-Tech 251 38-45
[3] Hammache M, Michaelian M and Browand F 2001 Aerodynamic forces on truck models
including two trucks in tandem California PATH Research Report
[4] Chilbule C, Upadhyay A and Mukkamala Y 2014 Analyzing the profile modification of truck-trailer to prune the aerodynamic drag and its repercussion on fuel consumption 12th Global Congress on Manufacturing and Management (Vellore) pp 1208-19
[5] Chowdhury H, Loganathan B and Mustary I 2016 Effect of various deflectors on drag reduction for trucks 1st Int Conf. Energy and Power (Melbourne) pp 561-6
[6] Wang Y G, Yang C, Yang Z G and Li Q L 2014 Analysis of aerodynamics noise of vehicle’s external surface Tech. Acoust. 33 50-5
[7] Ma D Y 2004 Modern Acoustics Theory (Beijing: Science Press) pp 293-8
[8] Zhang J, Sun B C, Guo T, Fang J and Zhao W Z 2015 Research on aerodynamic noise radiated from whole body surface of high-speed train and its distribution J. Chin. Rail. Soc. 37 10-7
[9] Luo Z M, Gu Z Q, Zong Y Q, Liu L G and Jiang C M 2016 Wind buffeting noise analysis and control for vehicle under crosswind Acta Aerodyn Sin. 34 468-75
[10] Huang S, Liang X F and Yang M Z 2012 Numerical Simulation of aerodynamic noise and noise reduction of high-speed train connection section Acta Aerodyn Sin. 30 254-9
[11] Zheng Z Y 2012 A study on the numerical simulation of high-speed vehicle’s external aerodynamic acoustic field (ChengDu: Southwest Jiaotong University)
[12] Proudman I 1952 The generation of noise by isotropic turbulence Proc. R. Soc. London, Ser. A, Mathematical and Physical Sciences 214 119-32
[13] Buchheim R, Marketzke J and Piatek R 1985 The control of aerodynamic parameters influence vehicle dynamics SAE Technical Paper Series 850279
[14] Sarkar S and Hussaini M Y 1993 Computation of the sound generated by isotropic turbulence (Washington, D.C.: NASAt Report) pp 74-93