Research on Vehicle Road Noise Simulation Based on Virtual Proving Ground Technique

Feng-ling GAO*, Nan ZHAN, Xiao-bing BU, Dong-liang GENG, Xiang-rong LI and Lin-lin WU
CAE Performance Division, Vehicle Crash Testing and Research Department, CATARC Automotive Test Center (Tianjin) Co., Ltd, Tianjin, China
*Corresponding author

Keywords: NVH, Virtual proving ground technique, CDTire.

Abstract. Using the virtual proving ground technique, CAE work can be put in front. Major performance problems of vehicles will be found and handled in advance to improve the research and development efficiency and reduce costs for automotive manufactures. However, this technique is relatively difficult to be implemented in NVH due to the complexity of tire modeling and other problems. Therefore, to deal with these issues, a complete simulation procedure for vehicle road noise was studied in this paper, in which PSD information of test road and CDTire model were integrated as the input of the whole vehicle simulation model successfully. The types of roads and tires, and tire mechanical parameters were compared investigated to provide useful suggestion to automotive manufacturers for NVH design.

Introduction

Noise, vibration and harshness, abbreviated as NVH, is a comprehensive problem to measure the quality of automotive manufacturing and gives the consumers the most direct feeling. The vehicle NVH problem is one of the most concerns of OEMs and component enterprises in the international automotive industry. Statistics show that about 1/3 of the vehicle breakdowns are related to the NVH problem, and nearly 20% of the research and development costs are spent on solving vehicle NVH problems [1,2].

Road noise is the direct or radiated noise produced by the contact between tires and the road as the excitation source when the vehicle is driving. It is one of the important research topics in NVH field [3]. The analysis of road noise is currently mainly based on the spindle load technique, in which acceleration response of knuckle recorded in the real vehicle road test and the transfer function from wheel center to knuckle obtained by FEM simulation are extracted to calculate the wheel center force as the stimulation input [4-6]. However, there are some defects in spindle load method. Firstly, it is difficult to achieve the full process forward development of vehicle due to the requirement for vehicle road test data, and the optimization space in the later stage is limited. Secondly, the characteristics of tire and road are ignored, which results in the sacrifice of simulation accuracy. It has been proved to be an effective way to handle the above issues by introducing the digital road and tire model into road noise simulation to establish the virtual proving ground (VPG) technique [7]. At present, the mainstream VPG road noise simulation method is based on modal tire model technical scheme [8,9]. In consideration of the low efficiency, the limited precision and the low generality in modal tire modeling, VPG technique has not been widely adopted in new vehicle development by domestic OEMs. CDTire is physical tire model considering geometric factors, which is appropriate in NVH analysis after linearization in view of its superior characteristics [10]. There have been successful application cases in road noise simulation using technique based on CDTire abroad. However, domestic studies in this area is rarely reported, lack of a complete technical scheme.

Therefore, in this paper, a VPG technique for vehicle road noise simulation was systematically investigated. In the next parts of this work, obtaining the PSD by testing the vertical distance of roads,
constructing CDTire model based on tire test and parameter identification, integrating vehicle road noise simulation model and discussing the calculation results will be introduced in detail.

**NVH Test Road Modeling**

The vertical displacement information of NVH test road is scanned by 4 laser sensors and other equipment installed on a mobile vehicle as shown in Fig. 1. During scanning, the speed of the mobile vehicle should be kept constant.

![Figure 1. NVH test road scanning.](image1)

After data post-processing, the power spectrum density (PSD) of the road that will be used in the following vehicle road noise simulation can thus be calculated by Eq. 1,

\[ S_q(n) = S_q(n_0) \left( \frac{n}{n_0} \right)^{-\omega} \]  

(1)

here, \( S_q(n) \) is the PSD of road flatness, and \( S_q(n_0) \) is the road flatness coefficient. \( n \) and \( n_0 \) represent the spatial frequency and reference spatial frequency, respectively. \( \omega \) denotes the index. Fig. 2 illustrates the calculated PSD of the rough big size asphalt road from the left wheel of the mobile vehicle.

![Figure 2. The left wheel PSD of the rough big size asphalt road.](image2)

**Tire Modeling by CDTire**

CDTire is a physical tire model which contains not only the mechanics information but also the geometry one. Based on a series of static, steady-state and dynamic tests on tires, CDTire model can be established after parameter identification (PI). The linearized CDTire model will be applied to conduct the vehicle road noise simulation. The flowchart of CDTire modeling is shown in Fig. 3.
In this work, a 245/45R19 tire is studied, which section scanned by CT and its corresponding geometry modeling is demonstrated in Fig. 4.

By combining optimization algorithm and engineering experience, all parameters of tire 245/45R19 (such as the cord layer stiffness, the distribution of damp and etc.) are identified finally by CDTire/PI software. Comparisons between test and simulation curves under some working conditions are given in Fig. 5, illustrating the PI results are reliable. Besides, the total error of simulation and test calculated by Eq. 2 is 0.18, meeting the requirement of CDTire modeling (less than 0.2).

\[
\text{error}(f, g) = L_p(f, g) = \frac{\|f - g\|}{\|f\|}
\]

with \(\|f\|_p = \left(\sum |f_p|^p\right)^{\frac{1}{p}}\), \(p = 1\) (2)

here, \(f\) and \(g\) are the response values on test curve and simulation curve, respectively.

**Vehicle Road Noise Modeling**

The models of trimmed body (including body, seat, steering system and sub frame), chassis (including front and rear suspension, and tires), powertrain system (including engine block, exhaust system and drive shaft) and cavity, are constructed respectively. Subsequently, these sub-assemblies are integrated by connectors with stiffness property to build the acoustic-solid coupling vehicle simulation model. After introducing road PSD as input excitation and setting the solution condition, the vehicle road noise simulation by virtual proving ground technique can be calculated according to Eq. 3.
Figure 5. Comparisons between test and simulation curves under some working conditions.
Response PSD = [TF]*[PSD]*[TF]*H

here, TF is the transfer function. The constructed vehicle road noise simulation model displayed by PLOTel elements is shown in Fig. 6.

Figure 6. The constructed vehicle road noise simulation model.

Results and Analysis

The simulated sound pressure level at the place of driver's outer ear is given in Fig. 7, in which the PSD of smooth big size asphalt road is taken as the input. Since NVH simulating software can not distinguish the cavity model of CDTire currently, the computed frequency in this paper is limited to 200 Hz. In addition, tire pressure of tire in this example is 2.3bar, and the speed of the vehicle is 50 km/h. Actual rim inertia and tire load also need to be conformed. As shown in Fig. 7, the cure of sound pressure level vs frequency is strongly nonlinear, and the peak value occurs at 110 Hz around resulted from the local mode of vehicle body.

Figure 7. The simulated road noise with the PSD input of the smooth big size asphalt road.

To study the effect of input source on the simulated sound pressure level, different types of roads and tires are compared to analyze here. Beside of the smooth big size asphalt road, the rough big size asphalt road and the smooth pave stones road are adopted as well. Fig. 8 (a) shows the comparison of the 3 roads, from which it is found that the road not only affects the frequency of noise inside the vehicle but also each peak value. It should be noticed that the maximum peak of sound pressure level from the smooth pave stones road is much more than the other roads. The reason is uncertain, and further research about TPA, MPA and ODS will be conduct in our next work. In addition, tires remarkable effect on the simulation results can be obtained from Fig. 8 (b). Therefore, if the OEM has multiple alternative tires, each tire needs to be tested and modeled by CDTire to ensure the simulation accuracy.
By building the corresponding relationship between tire parameters and vehicle road noise, some guidance could be provided to automotive manufacturers to choose tires for their new developed vehicles. In this part, as an example, two tire parameters—the bandage layer stiffness and rubber stiffness are studied by approximate sensitivity analysis. Fig. 9 gives the comparison results based on tire 245/45R19 (The road is the same smooth big size asphalt). The change steps of bandage layer stiffness and rubber stiffness are 100 N/mm and 1N/mm, respectively. It is found that the stiffness of bandage layer and rubber has no effect on the frequency of vehicle road noise, but influence the amplitude of sound pressure level (especially when the frequency is greater than 130 Hz). When the frequency is lower than 130 Hz, less bandage layer stiffness will give rise to more load noise. It is the opposite when the frequency is over 130 Hz. As for rubber stiffness, it almost has the same trend as the bandage layer stiffness. Note that when the stiffness value increases to a certain extent, the influence on the road noise is not obvious. Due to there are more than 100 parameters to a CDTire model, much more works needs to be conducted to study the parameter sensitivity. Consequently, more detailed regularities will be summarized in our future research.

Summary

CAE is an important tool to conduct vehicle NVH study. In order to solve the road noise simulation more accurately and efficiently, a virtual proving ground technique for vehicle road noise simulation was studied in this work. Vertical distance of NVH test road was measured first, and the PSD of such road could thus be calculated conveniently. Parameter identification by CDTire was investigated systematically to construct tire model. By connecting the road PSD, CDTire model and the vehicle FEM model, the entire simulation technique would be successfully conducted. The comparison research showed that the types of roads and tires have great influence on the simulation results. The effects of bandage layer and rubber stiffness on sound pressure level were studied as well, which would provide useful tire selection suggestion to OEM.
Acknowledgement

This research was financially supported by the Research on common basic technology of CATARC Automotive Test Center (Tianjin) Co., Ltd (NO. TJKY1920010 and NO. TJKY1920011).

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