Structural transfer path analysis of automobile tire/road noise

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ABSTRACT

With refinement of powertrain, tire/road induced noise has become an important parameter within vehicle development. It is necessary to reveal the transfer characteristics of tire/road noise for suppressing it. This paper presents an experimental analysis of the structural-borne contribution of noise and vibration for a vehicle driving on a coarse road, using a simplified transfer path analysis method (TPA).

The simplified TPA method is used to identify the major noise transfer paths of tire/road noise based on subjective evaluation and objective measurement, which is fast and cost-saving compared with conventional TPA method. The vehicle tire/road noise is analyzed by the simplified TPA method, which shows the rear suspensions are the major contribution components. A TPA model for the rear suspension noise and vibration is built up and the transfer path testing is carried out. The comparison of measured and recalculated interior sound pressure level shows a good correlation. The results show Z- direction of the torsion beam axle and Z- direction of the left shock absorber are significant contribution paths to the interior noise. To improve the tire/ road noise and not to sacrifice the side effects such as handling and durability, the torsion beam axle structure is modified.

Keywords**:** transfer path analysis (TPA); exciting force; tire/ road noise I-INCE Classification of Subjects Number(s): 30

1. INTRODUCTION

Reduction of vehicle noise and refinement of sound quality is becoming more important for occupant comfort. With the quick development of powertrain noise reduction, tire/road noise has become increasingly important referring to overall acoustic comfort. The tire/road noise dominates the interior noise of today's cars during middle constant speed with low load on coarse roads [1, 2].

Tire/road noise is divided into three frequency categories: low-frequency noise (0-100Hz), mid-frequency noise (100-500Hz) and high-frequency noise (above 500 Hz). Low frequency noise is easy to induce the passenger discomfort, such as nausea, vomiting during riding.

With the increasing of people's living standard, the noise environment has also heightened, and the traffic noise regulations have been more and more strict year by year. Sound barriers and low-noise smooth roads are used to r[1]educe noise pollution. For air-borne noise, Yum et al [3, 4] studied the influence of tire size and shape on sound radiation in the mid-frequency region. They identified the relationship between the structural wave propagation characteristics of a tire excited at one point and its sound radiation using FE and BE analyses. Naoko Yorozu et al [5] identified the condition to reduce mid-frequency sound by focusing on the mechanism to reduce particle velocity as the sound absorption principle of acoustic materials. They derived the specific structure to realize this condition in order to reduce road noise. For structure-borne noise, Ichiro Kido et al [6] analyzed the coupled vibration between suspension and tire/wheel and to improve their vibration, and a rumble noise around 160Hz was solved by this method. Helium is used to "eliminate" excitation sources at the frequencies of tire cavity resonances, thereby reducing the number of paths to consider and simplifying a complex multi reference TPA down to a single-reference TPA problem by Waisanen et al [7].

The objective of this paper is to study the influence of low-frequency tire/road noise on interior rumble noise. Firstly, the contributions of each structural transmission paths from the suspension to the vehicle body for the rumbling noise frequency are identified and ranked. Next, the problem of tire/road noise is successfully resolved by modifying the twist beam structures, which production cost is reduced by avoiding adding sound-absorbing materials on the vehicle body.

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2. TIRE/ROAD NOISE TRANSFER PATH ANALYSIS

2.1 Tire/road Noise Characterization

Tire/road noise generally fall into two categories: one category comes directly from tire radiation noise, called airborne noise or directly transmitted noise; Another category is called structural borne noise, where vibration transfers through chassis to body and radiates noise [8, 9]. The transfer paths diagram of the tire/road noise is shown in figure1.

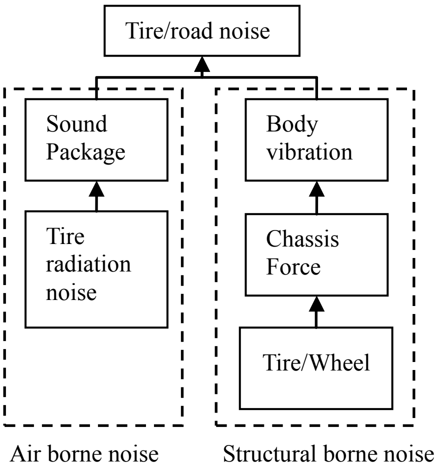

Fig1. The transfer paths of the tire/road noise

Air borne noise is influenced by two factors. One is the level of radiation noise generated during tire/road interaction, and the other is the acoustic performance of vehicle body sealing.

Structural borne noise is influenced by three factors, firstly, transfer function of tire/road force, secondly, tire/wheel exciting force attenuation and transfer characteristics of suspension, and the last is attachment point dynamic stiffness and sensitivity of body [10, 11]. This paper only focuses on the structural transfer path analysis of the tire/road noise.

2.2 Structure Transfer Path of Tire/road Noise

The tire and road surface interaction forces generated by vehicle motion enter the body through the suspension links and cradle, and are coupled with acoustic cavity, which creates the noise perceived by passenger. A system model, where tire/wheel is used as exciting source and sound pressure inside the car is the target or output system, is shown in figure 2 (the model is suitable for the independent type front suspension, and torsion beam axle type rear suspension).

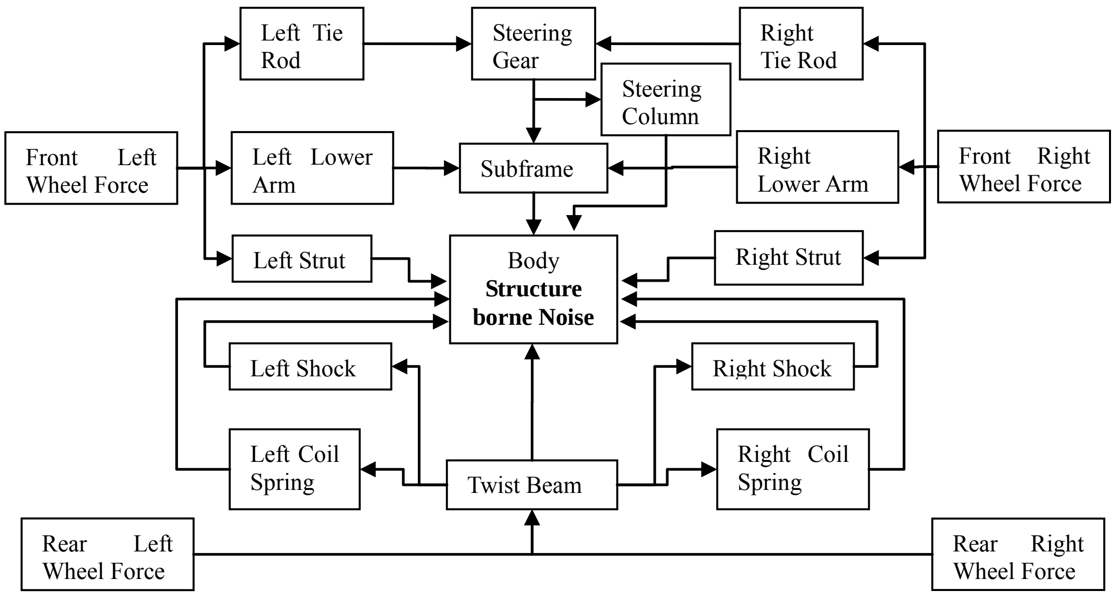

Fig2. Diagram of tire/road noise structural transfer paths

Figure 2 shows that road/tire noise has a number of transfer paths, which takes a large amount of time and expense to test one by one. In practice, therefore, the work efficiency needs to be improved by taking some measurements to narrow down the scope of the transfer paths.

2.3 Interior Noise Calculation

Based on the assumption of linear system, the total interior sound pressure ‘ P_{str} ’ at a given receiver location can be written as a summed contribution of the partial sound pressures ‘ P_i ’, related to each given transfer path ‘i’ [12]:

$$P_{str} = \sum_{i=1}^{n} P_i \tag{1}$$

The determination of these partial sound pressures is based upon the combination of an estimate of operation force ‘ F_i ’ in the given transfer path and the noise transfer function ‘ H_i ’ between interior sound pressure response and a unit force applied at the body side of the considered transfer path.

$$P_{str} = \sum_{i=1}^{n} \frac{P_i}{F_i} \cdot F_i = \sum_{i=1}^{n} H_i \cdot F_i \tag{2}$$

Assuming there are 'm' transfer paths, the summed interior sound pressure $\{P\}$ can be calculated by multiplying the transfer function matrices $[H_{mn}]$ and excitation forces:

$$\{P\} = [H_{mn}]\{F\} \tag{3}$$

There are four methods to measure the operation forces: direct measurement, complex stiffness method, matrix inversion method and driving point inversion [13, 14]. The matrix inverse method, also known as impedance matrix method, is the most commonly applied in road TPA and also used in this paper.

For a linear system, the operational forces $\{F\}$ may be estimated by the following equation:

$$\{F\} = [H_{mn}]_{FRF}^{-1} \times \{X\} \tag{4}$$

Where $$[H_{mn}]_{FRF}^{-1} = \begin{bmatrix} \frac{X_{11}}{F_1} & \frac{X_{12}}{F_1} & \cdots & \frac{X_{1n}}{F_1} \\ \frac{X_{21}}{F_1} & \frac{X_{22}}{F_1} & \cdots & \frac{X_{2n}}{F_1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{X_{m1}}{F_n} & \frac{X_{m2}}{F_n} & \cdots & \frac{X_{mn}}{F_n} \end{bmatrix}_{FRF}^{-1}$$

And $\{X\}$ is the operational vibrations measured at the passive side (body).
Then, the interior sound pressure can be written as:

$$\{P\} = [H_{mn}][H_{mn}]_{FRF}^{-1} \times \{X\} \tag{5}$$

3. TIRE/ROAD NOISE TRANSFER PATH OPTIMIZATION

The rumble noise is one kind of tire/road noises. The unpleasant and deep low frequency sound is most noticeable at low and middle vehicle speed on coarse road. This paper describes a procedure to reduce rumble noise to an acceptable level in the vehicle where an independent front suspension and a torsion beam axle type rear suspension are used.

3.1 Transfer Path Simplification

After subjective evaluation, it is found that the vehicle has clear rumble noise when running at 50 km/h in cement coarse road. Subjective evaluation shows that the rumble noise at the rear passenger location is more severe. In order to confirm the rumble noise transfer path, the PCA (Principal Component Analysis) is used to confirm the front and rear suspensions' contribution, as shown in figure 3.

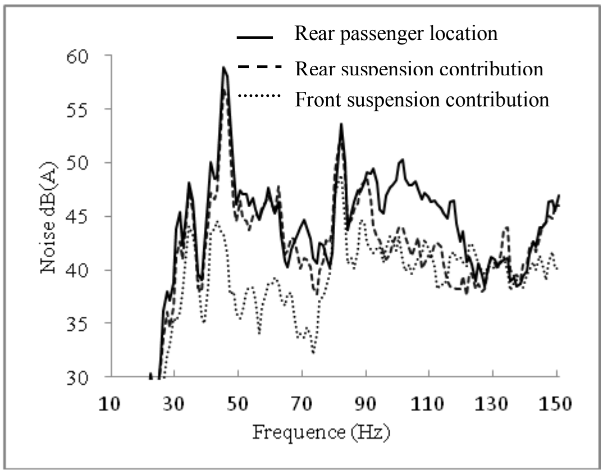

Fig3. Front/rear suspensions' contribution

Figure 3 shows that there is a big peak of the interior noise at 50 Hz, and the rear suspension is the major contribution. Therefore, the transfer paths of tire/road noise shown in figure 2 can be reduced to figure 4.

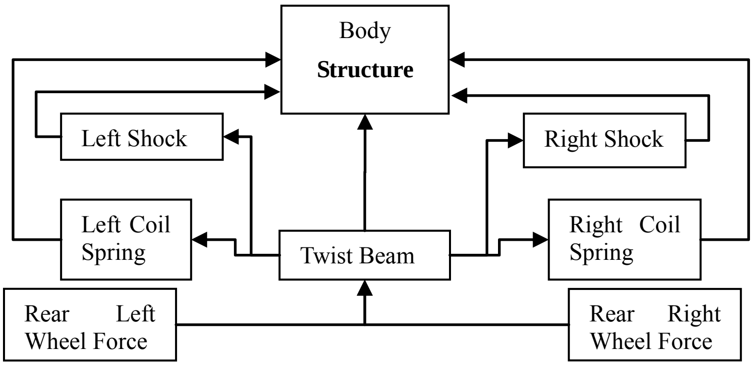

Fig4. Diagram of the reduced rumble noise transfer paths

Figure 4 shows the rumble noise has 6 paths: left rear coil spring, left rear shock, right rear coil spring, right rear shock, and the both sides of twist beam to the car. Thus, the 6 attachment points of body are defined as the exciting points, and only three translational degrees (x, y, z) for each point are considered and the rotational degrees are ignored. The total transfer paths are 6 * 3 = 18.

According to Equation (5), the contribution of above 18 paths to the interior noise can be calculated as:

$$\begin{Bmatrix} P_1 \\ P_2 \\ \vdots \\ P_{18} \end{Bmatrix} = \begin{bmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,18} \\ H_{2,1} & H_{2,2} & \cdots & H_{2,18} \\ \vdots & \vdots & \ddots & \vdots \\ H_{18,1} & H_{18,2} & \cdots & H_{18,18} \end{bmatrix} \begin{bmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,18} \\ H_{2,1} & H_{2,2} & \cdots & H_{2,18} \\ \vdots & \vdots & \ddots & \vdots \\ H_{18,1} & H_{18,2} & \cdots & H_{18,18} \end{bmatrix}_{FRF}^{-1} \times \begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{18} \end{Bmatrix} \tag{6}$$

Where $H_{1,1}$, $H_{1,2}$, …, $H_{18,18}$ are noise transfer functions between the rear passenger ear pressure and the exciting force applied at the body side, $H_{1,1\,\mathrm{FRF}}$, $H_{1,2\,\mathrm{FRF}}$, …, $H_{18,18\,\mathrm{FRF}}$ are the transfer functions between the response of X_i and the exciting force applied at the body side, and X_1, X_2,… , X_{18} are the vector of operational accelerations measured on the body side of the interface.

3.2 Path Identification/ranking

The rear passenger ear pressure level can be calculated by substituting the measured $\left[H_{mn}\right]$, $\left[H_{mn}\right]_{FRF}$ and $\{X\}$ into equation (6). The calculated sound pressure is then compared with the measured operational sound pressure, as shown in figure 5.

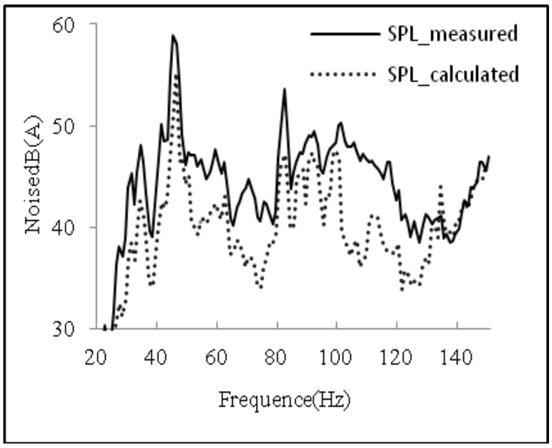

Fig 5 Calculated vs. measured SPL at rear passenger ear

The reasonably good agreement at 50 Hz between the calculated and measured sound pressure shown in Figure 5 proves that the paths are sufficient to demonstrate the validity of the sound pressure calculated using equation (6). Each path contribution to the interior noise at 50 Hz is shown in figure 6.

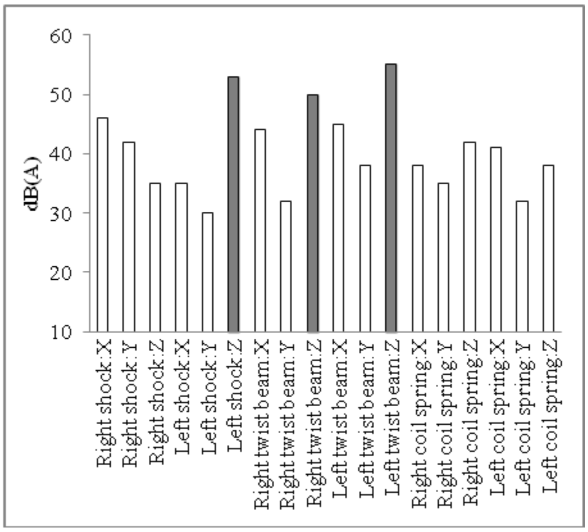

Fig 6 TPA path contribution map

Figure 6 show that three paths have very high contributions, and all three are similar in strength. These three high contribution paths are the both sided of twist beam and the left shock.

Similarly, contribution map is used to identify and rank the individual direction contributions for each significant connection. For the both sides of twist beam, the Z-direction (vertical) is the strongest. For the left shock, the Z-direction (vertical) is significant.

3.3 Structure Optimization

Structural-borne noise is determined by the operation force and the transfer function. This paper attempts to reduce the rumble noise by controlling the contribution of exciting forces. Therefore, the improvement direction is to reduce the forces excited by the twist beam on the body.

The mount bush stiffness has significant impact on the isolation performance of the twist beam. The isolation performance is improved and the interior noise is reduced by reducing the mount bush stiffness, but it cripples handling performances. To improve the rumble noise and not to deteriorate the side effects such as handling and durability, the angle of twist beam is modified. Adjusting the bushing in Y direction will reduce the bushing stiffness, and simultaneously good handling performances can be guaranteed. The modification of twist beam is shown in figure 7.

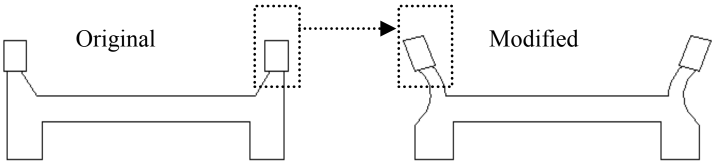

Fig 7 Modification of twist beam

Test results of the modified twist beam are shown in Figure 8.

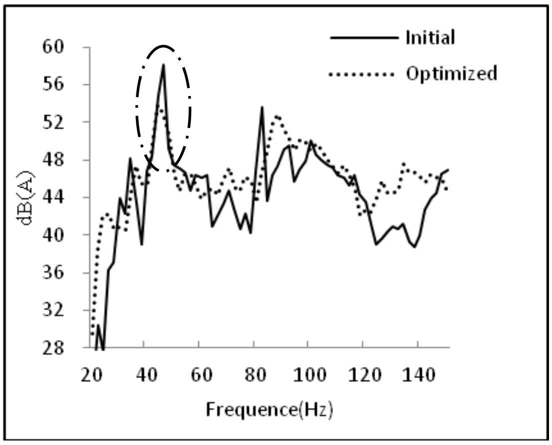

Fig 8 Twist beam modification effect on interior noise

Figure 8 shows that interior noise is reduced by 4 dB (A) at 50 Hz after the twist beam structure is modified, and the structural-borne noise transfer path is controlled effectively, then the rumble noise is solved successfully. The interior noise is acceptable by modifying the twist beam structure only, so the path of left shock is not needed to be optimized.

4. CONCLUSIONS

Based on the chassis exciting forces and their transfer paths, the structural transfer paths of tire/road noise are analyzed, and the corresponding responses and excitations are tested. The basic conclusions are summarized below:

1）Inverse matrix method is used to estimate the coupling exciting force of each transfer path, and interior noise is calculated, the calculation results agree well with the measured results.

2）The contributions of each path to the interior noise are analyzed by using spectrum contribution cloud image. Results show that the contribution of Z-direction of torsion beam axle and Z-direction of left shock to interior noise are significant paths.

3）The exciting force of the twist beam to the body is reduced by modifying twist beam structure, and interior rumble noise is solved successfully.

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