DEVELOPMENT OF ROAD NOISE ESTIMATION TECHNOLOGY BASED ON CHARACTER OF TIRE AND MATRIX INVERSION METHOD

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ABSTRACT

Quantification of road noise is a challenging issue in vehicle NVH due to extremely complicated transfer paths of road noise as well as the difficulty in an experimental identification of input force from tire-road interaction. In this paper to estimate input force, measured acceleration during driving and inversed tire frequency response functions are used. Also, a vehicle transfer function between the ear point and axle was measured by acoustic excitation. The total system transfer function was calculated by inversion and multiplication of three frequency response functions. In the inversion procedure, a Tikhonov regularization method was used in order to reduce inversion error. From the proposed method, it was able to evaluate each contribution of tire to road noise.

1. INTRODUCTION

Identification of the noise source of vehicles is the start of development for low-noise vehicles. Dominant sources that contribute to interior noise are power-train, manifold and road noise which is generated by interaction between road and tire. In these sources, road noise is most influential to interior noise [1,2]. Power-train and manifold noise are have been greatly reduced but road noise remains a big noise relatively [3]. So quantification of road noise becomes influential in the vehicle NVH area. But experimentally measuring of excitation force is difficult and transfer paths of road noise are very complicated.

Interior road noise is the result of interaction between road and tire. Road noise is mainly generated below 500 Hz, and has a peak at 60 ~ 65 dBA. Above 250 Hz, the SPL (Sound Pressure Level) decreases with increasing of frequency. Higher than 1 kHz, the SPL is 15dBA lower than the SPL at 300 Hz, so the contribution to interior noise is extremely decreased [4].

In this paper FRFs (Frequency Response Function) are measured to define the influence of tire character and to obtain transfer path information. Driving test accelerations of the tire at the knuckles are also measured. The knuckle is the part of the axle nearby the tire wheel. Finally, road noise is estimated by combining FRF and acceleration, using the vibro-acoustic reciprocity, matrix inversion method.
2. DEVELOPMENT OF ESTIMATING MODEL

To develop the estimating model, the estimated excitation force and FRF of each transfer path are combined. In this section, excitation force is estimated by vibro-acoustic reciprocity and matrix inversion method. This approach is valid for linear systems, so the tire-road contact is assumed to be a linear model. To combine the force and FRF, the matrix inversion method and regularization are used.

2.1 ESTIMATION OF EXCITATION FORCE

At the leading edge of the tire, measuring of excitation force is impossible because of the lack of measuring placement. So the excitation force is estimated by vibro-acoustic reciprocity. Acceleration at the leading edge $\dot{x}_{le}$ is obtained by excitation at the knuckle $f_{kn}$. Using vibro-acoustic reciprocity, this is converted as in eq. (1).

$$\dot{x}_{le} = H_{le/kn} \times f_{kn} \Rightarrow \dot{x}_{kn} = H_{le/kn} \times f_{le}$$

$H_{le/kn}$ is FRF between the knuckle and the leading edge. The excitation force at the leading edge $f_{le}$ is obtained by applying the matrix inversion method at eq. (1).

$$f_{le} = H_{le/kn}^{-1} \times \dot{x}_{kn}$$

Eq. (2) is result of the matrix inversion. The excitation force $f_{le}$ is obtained through combining the inversed FRF $H_{le/kn}^{-1}$ and acceleration at the knuckle $\dot{x}_{kn}$.

2.2 ESTIMATION OF ROAD NOISE

To estimate road noise, the excitation force is calculated with the FRF of transfer path. The first transfer path is the knuckle to wheel center. The FRF of this path is measured by excitation at knuckle $f_{kn}$ and measured acceleration at wheel center $\dot{x}_{wc}$. By apply vibro-acoustic reciprocity, the knuckle to wheel center transfer path is calculated as:

$$\dot{x}_{wc} = H_{wc/kn} \times f_{kn} \Rightarrow \dot{x}_{kn} = H_{wc/kn} \times f_{wc}$$

The second path is the wheel center to the interior cabin. To measure the FRF of this path, an acoustic exciter is used. The input is the volume acceleration of exciter $q_c$, and the output is the acceleration at the wheel center $\dot{x}_{wc}$. Like eq. (3), reciprocity is also applied to this FRF.

$$\dot{x}_{wc} = H_{wc/c} \times q_c \Rightarrow p_c = H_{wc/c} \times f_{wc}$$

The final model in eq. (5) is calculated with eq. (1), (3) and (4).

$$p_c = H_{wc/c} \times H_{wc/kn}^{-1} \times H_{le/kn} \times f_{le}$$
3. MEASUREMENT FOR FRF OF TIRE AND VEHICLE

In this section, experiments for measuring each data are described.

3.1 TIRE VIBRATION CHARACTER TEST

To define the tire vibration character, a modal test is carried out. Fig. 1 is the setup for the modal test and FRF. The hydraulic exciter is assumed to model a rigid road. The hydraulic exciter is sufficiently rigid so the device acts in the same way as the road excitation. A quarter of the vehicle load of 4000 N is applied by the exciter, and nine accelerometers are attached circumferentially around the tire. Fig. 2 shows the mode shapes of the tire.

![Experimental setup for modal test and FRF](image1)

![Mode shapes for the tire](image2)

Figure 1. Experimental setup for modal test and FRF

Figure 2. Mode shapes for the tire (a) 1st mode at 68.4 Hz, (b) 2nd mode at 90.8 Hz, (c) 3rd mode at 116.6 Hz, (d) 4th mode at 142.9 Hz

When the tire and rim are assembled, there is a cavity inside the tire. Noise of the cavity contributes to the road noise. To calculate its resonance frequency, it is assumed the cavity acts as a duct model as in Fig. 3

![Illustration for cavity duct model](image3)

Figure 3. Illustration for cavity duct model

$L_1$ is the width of the tire, $L_2$ is the circumference of the tire, $L_3$ is the inside radius of the cavity. The resonance frequency is described by eq. (6)

$$f_n = \frac{c_0}{2\pi} \sqrt{\left(\frac{n_1 \pi}{L_1}\right)^2 + \left(\frac{n_2 \pi}{L_2}\right)^2 + \left(\frac{n_3 \pi}{L_3}\right)^2}$$  \hspace{1cm} (6)

Calculation of eq. (6) gives a frequency of 220 Hz.
3.2 MEASUREMENT OF FRF TEST AT TIRE

To measure FRF $H_{le/kn}$, $H_{wc/kn}$ of the tire section, a quarter model of the vehicle is used. The input force $f_{kn}$ acts at the knuckle with vertical and driving direction (red point of Fig. 4) using an impulse hammer. Output accelerations $\ddot{x}_{le}$, $\ddot{x}_{wc}$ are measured at the leading edge and wheel center of the tire with same direction of impact. In this measurement, 3-axis accelerometers are used. To match the driving condition, a quarter load of the vehicle is added. Fig. 4 shows the excitation and measurement points. In Fig. 4, the measurement setup uses a simple model of the tire and knuckle. The reason for using a simple model is that impact testing is impossible in the real model due to limited space.

![Figure 4. Excitation and measurement point for the FRF test.](image)

Fig. 5 shows the FRF at each point. The peak at 220 Hz of $H_{le/kn}$ is the result of the cavity resonance. The peak at 90 Hz of both FRFs is second mode of tire vibration.

![Figure 5. FRF between the knuckle and the tire](image)

3.3 MEASUREMENT OF FRF TEST AT VEHICLE

The FRF between the wheel center-cabin $H_{wc/c}$ is measured using an acoustic exciter. The omni-directional acoustic exciter is placed on the driver seat and generates volume acceleration $q_c$. To measure acceleration at wheel center, the tire is removed and accelerometer is attached at each wheel center. That is, 4 FRFs between wheel center-cabin are measured. In this test, couplings between each FRF are neglected. To exclude interaction with the floor, rubber packs are added between the vehicle and the car lift. Fig. 6 shows the setup for the FRF test at vehicle, while Fig. 7 shows the wheel center-cabin FRF $H_{wc/c}$.
Figure 6. Experimental setup for FRF test at vehicle

Figure 7. FRF between the wheel center and the cabin

3.4 DRIVING TEST

In the driving test, the acceleration at the knuckle $\ddot{x}_{kn}$ and road noise $p_{ref}$ are measured. $\ddot{x}_{kn}$ is needed for the estimation of excitation force $\mathbf{f}_{le}$, and $p_{ref}$ is reference data. 3-axis accelerometers are attached at each knuckle and a microphone is installed at the driver’s ear position, as shown in Fig. 8. The accelerations are measured in the vertical and driving directions. Knuckle positions are determined as closely as possible to those shown in Fig. 4. The driving velocity is 60 km/h, and measuring time is 10 sec.

Figure 8. Experimental set up for driving test

4. ESTIMATION OF EXCITATION FORCE AND ROAD NOISE

In this section, the excitation force and road noise are estimated through measured data in the above section. In this process, regularization is applied by the matrix inversion method to decrease ill-conditioning errors. Tikhonov regularization is selected amongst various regularization methods [5]. In this method, the regularization parameter is determined by GCV (Generalized Cross Validation) method.
4.1 ESTIMATION OF EXCITATION FORCE

The excitation force is estimated with an operational acceleration at the knuckle (see section 3.4) and the FRF at the tire (see section 3.2) using eq. (2). Fig. 9 shows the estimated excitation force at the knuckle $f_{exc}$. Dominant excitation frequencies are 25, 50, 90 and 210 Hz.

![Figure 9. Estimated force at knuckle after regularizing processing](image)

4.2 ESTIMATION OF ROAD NOISE

Estimation of road noise is performed by calculation using the estimated excitation force (see section 4.1) and the FRF at both positions (see sections 3.2 and 3.3). In this process, 4 tire’s FRFs are assumed to be the same. Fig. 10 shows a comparison of the estimated road noise and the measured road noise in section 3.4.

![Figure 10. Comparison of estimated and measured road noise](image)

Peaks of both road noise spectra are similar at 90 and 220 Hz. The peak at 90Hz is the second mode of the loaded tire (see section 3.1). The peak at 220 Hz is the cavity mode calculated in section 3.1. This comparison shows that characteristics of the tire are well reflected and dominant components of the generated road noise at those frequencies.

Errors at other frequencies are caused by other input sources without interaction between road and tire leading edge. Measured road noises include sources caused by the powertrain, manifolds, wind and road noise. If the interior noise caused by other acoustic sources are estimated and summed, the estimated noise is expected to more closely follow the measured noise.
5. CONCLUSIONS

The purposes of this paper are the estimation of road noise and to define the influence of the character of tire. To estimate excitation force and road noise, FRFs measured at each position and operational acceleration at the knuckle are measured. To calculate these, data matrix inversion method is applied. The matrix inversion method applied uses Tikhonov regularization to decrease ill-conditioning errors. In comparison with measured road noise, peaks caused by the character of tire are shown at 90 and 220Hz. In this paper, transfer paths are chosen knuckle–wheel center–cabin route, but to better estimate road noise, more paths should be considered. Influences of other paths are examined continuously.

REFERENCES


