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NEW TECHNIQUE IN THE USE OF VIBRO−ACOUSTICAL RECIPROCITY WITH APPLICATION TO THE NOISE TRANSFER FUNCTION MEASUREMENT

K.-H. KO[2], H. S. KOOK[1]* and S.-J. HEO[1]

[1]Graduate School of Automotive Engineering, Kookmin University, Seoul 136-702, Korea
[2]R&D Center, mPlus Corporation, 124-21 Banjeong, Taeahn-eub, Hwaseong-si, Gyeonggi 445-972, Korea

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ABSTRACT−A noise transfer function (NTF) is the frequency response function between an input force applied to an exterior point of a vehicle body and the resultant interior sound pressure usually measured at the driver's ear position. It represents the measure of noise sensitivity for the output force transmitted to the joints between the body and chassis. The principle of vibro-acoustic reciprocity is often utilized in the measurement of NTF. One difficulty in using the volume source is that most of the previously proposed methods require the knowledge of the volume velocity of the acoustic source in advance. A new method proposed in the present work does not require any calculation related with the volume velocity of the acoustic source, but still yields even more accurate results both in the amplitude and phase of the NTF. In the present work, the new method is applied to obtain NTF data for a midsize sedan.

KEY WORDS : Noise transfer function, Vibro-acoustic reciprocity

1. INTRODUCTION

A vehicle body is connected with chassis components such as engines, drive trains and suspensions. Representative connecting parts are engine mounts, suspension bushes, shock absorber bushes, sub frame mounts, and exhaust muffler mounts. Structure-borne noise is the interior noise that results from the vibrational energy (usually at low frequencies below 500 Hz) transmitted through those connecting parts between the body and chassis, and it is often called “booming noise” when the vibrational energy resonates the structural vibration modes of the body panels or the acoustic cavity modes of the vehicle compartment. Thus, it is essential, in order to reduce the interior noise, to first evaluate the contributions of the noise sources from the various noise transfer paths and then to identify the major noise contributors among them (Tsuge *et al.*, 1985; Wyckaert and Van der Auweraer, 1995; Gu and Juan, 1997).

The noise transfer function represents the characteristics of the transferred interior noise due to the vibrational force applied at a body-chassis connecting point, and thus can be obtained by measuring the frequency response function between the acoustic response (usually measured at the driver’s right ear position) and the input applied force at a connecting point (Ko *et al.*, 2003). Conventionally, impact hammer tests have been performed to measure the noise transfer functions. Impact hammer test is, however, not a practical method for the cases such as when the target position is not easily accessible, when there is no enough room for impact-hammering, and when it is difficult to hammer in some directions at the target point (for instance, in the tangential directions of surfaces).

In theory, vibro-acoustical reciprocity can be used in such cases to yield the same results. In the methods based on the vibro-acoustic reciprocity, a volume source is positioned at the microphone’s position as an input signal, while the output velocity is measured at the input force position in the impact hammer test (Linden *et al.*, 1993; Hendricx *et al.*, 1997). One practical issue in obtaining the vibro-acoustic transfer functions by measuring the vibration response due to an acoustic excitation is about obtaining the magnitude and phase of the volume velocity (i.e., source strength) as a function of frequency. Measuring the volume velocity of an acoustic source is also needed in other areas (for instance, in measuring acoustic transfer impedances, and in finding generated power of an acoustic source).

Ih and Kim (1993) used the principle of vibro-acoustic reciprocity to calculate the volume velocity of an acoustic source, while several other techniques utilize direct

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**Corresponding author.* e-mail: kook@kookmin.ac.kr measureent such as laser velocimetry, internal pressure measurement, and so on. To obtain average source strength, Ih and Kim used the vibro-acoustic reciprocity at multiple reference input points and verified their approach by experimentally showing the validity of the principle of vibro-acoustic reciprocity at other points.

In the present work, a similar approach is followed to Ih and Kim's (1993) in the sense that the source strength is "calibrated" by comparing with a corresponding impact hammer test data based on vibro-acoustic reciprocity. However, instead of formulating for the source strength, a simple and convenient formulation for directly calculating the noise transfer functions is attempted for practical purpose. The formulation is presented in terms of frequency response functions between the acceleration signals that are directly obtainable from any frequency analyzers, and a reference point is carefully chosen on the vehicle body surface used in the test.

2. NOISE TRANSFER FUNCTIONS AND VIBRO-ACOUSTICAL RECIPROCITY

The noise transfer function, $H_{ki}(\omega)$, between the input force applied at point i and the output acoustic response at point k can be represented as

$$H_{ki}(\omega) = \frac{p_k(\omega)}{f_i(\omega)} \tag{1}$$

where $p_k(\omega)$ and $f_i(\omega)$ are noise and force spectrum, respectively, at each point. In linear systems, there exists a reciprocal relationship, and equation (1) can be represented as (Fahy, 1985)

$$\frac{p_k(\omega)}{f_i(\omega)} = \frac{v_i(\omega)}{Q_k(\omega)} \tag{2}$$

where $v_i(\omega)$ is the velocity that would be obtained at point i, if an acoustic source with a source strength $Q_k(\omega)$ were positioned at point k without force applied at point i. The frequency response function, (v_i/Q_k), can equivalently be represented as

$$H_{ki}(\omega) = \frac{S_{Q_k v_i}(\omega)}{S_{Q_k Q_i}(\omega)} \tag{3}$$

where $S_{Q_k v_i}(\omega)$ is the cross power spectrum between the acoustic volume velocity at point k and the velocity at point i, and $S_{Q_k Q_i}(\omega)$ is the auto power spectrum of the volume velocity.

Similarly, a noise transfer function, between the input force at a different point j and output acoustic response at the response point k, can be represented as

$$H_{kj}(\omega) = \frac{S_{Q_k v_j}(\omega)}{S_{Q_k Q_i}(\omega)} \tag{4}$$

Auto power spectrum, $S_{Q_k Q_i}(\omega)$, can be removed by combining equations (3) and (4), and $H_{ki}(w)$ can be related with $H_{kj}(\omega)$, i.e.,

$$H_{ki}(\omega) = \frac{S_{Q_k v_i}(\omega)}{S_{Q_k v_j}(\omega)} H_{kj}(\omega) \tag{5}$$

The ratio of the two cross power spectrums in equation (5) can be simplified as

$$\begin{aligned} \frac{S_{Q_k v_i}(\omega)}{S_{Q_k v_j}(\omega)} &= \frac{Q_k^*(\omega) v_i(\omega)}{Q_k^*(\omega) v_j(\omega)} = \left.\frac{v_i(\omega)}{v_j(\omega)}\right|_{\Omega_k} \\ &= \left.\frac{a_i(\omega)}{a_j(\omega)}\right|_{\Omega_k} = H_{ij}^a(\omega)|_{\Omega_k} \end{aligned} \tag{6}$$

where $H_{ij}^a(\omega)|_{\Omega_k}$ denotes the measured ratio of the acceleration at point i to the acceleration at point j, when the acoustic source at point k with a source strength $Q_k(\omega)$ is on. In the present work, $H_{ij}^a(\omega)|_{\Omega_k}$ is called "acceleration ratio" function. Note that the acceleration ratio is independent of the source strength, but dependent on the position of the acoustic source. By substituting equation (6) into (5), a final form of $H_{ki}(\omega)$ can be obtained as

$$H_{ki}(\omega) = H_{ij}^a(\omega)|_{\Omega_k} \cdot H_{kj}(\omega) \tag{7}$$

Equation (7) can be used to determine the noise transfer function from input force at point i to response pressure at point k by performing the corresponding reciprocal test, provided that $H_{kj}(\omega)$ is known. The input force point j can be chosen at such points that impact hammer test can easily be performed to obtain a "reference" noise transfer function $H_{kj}(\omega)$. Once the noise transfer function $H_{kj}(\omega)$ is obtained at the reference point j by performing an impact hammer test, only the frequency response functions at each input point with respect to the reference point j (i.e., acceleration ratios) are need to be measured in the corresponding reciprocal test with the acoustic source at point k on. Since the acceleration ratio function is independent of the volume velocity of an acoustic source, any acoustic sources can be placed at point k as long as they can be considered monopole sources within the frequency range of interest.

3. NOISE TRANSFER FUNCTION MEASUREMENT

To evaluate noise sensitivity of the driver's ear position due to road input forces transmitted through various body-suspension mount parts, noise transfer function measurement was performed by using an acoustic source and accelerometers. The test vehicle is a front-engine and front-wheel drive car. Front is MacPherson strut independent suspensions, while rear is dual link type. The body-

Table 1. noise transfer function measurement points (the mounts with gray background belong to the rear suspension).

No.	Input point
1	front strut mount LH
2	front strut mount RH
3	rear strut mount LH
4	rear strut mount RH
5	front sub frame LH - upper
6	front sub frame RH - upper
7	front sub frame LH - lower
8	front sub frame RH - lower
9	trailing link LH
10	trailing link RH
11	rear sub frame LH - front
12	rear sub frame RH - front
13	rear sub frame LH - rear
14	rear sub frame RH - rear

suspension mount paths considered in the test are shown in Table 1.

At each point, three noise transfer functions associated with a pre-defined three orthogonal directions were obtained, thus making total of 42 noise transfer paths. The three axes of the coordinate system are fore/aft (x-direction), lateral (y-direction), and vertical (z-direction) directions of the test car, respectively. Acceleration signals in the x-, y-, and z-directions on a mount point were simultaneously collected by using a three-axis accelerometer. A three-axis accelerometer glued to the right front strut mount for data acquisition is shown in Figure 1.

To make the reciprocal measurement procedure easier, an acoustic source was devised in the present work. It is designed especially for the reciprocal measurement of the noise transfer functions in vehicles. The acoustic source placed at the driver's seat of a mid size sedan is shown in figure 1. The height of the closed enclosure was determined so that the diaphragm of the loudspeaker can be placed approximately at the driver's ear position when the enclosure is seated at the driver's seat. The maximum input power of the loudspeaker unit is 150W, and the frequency range of 5dB bandwidth of the acoustic source was measured to be approximately from 40 to 2000 Hz. Inside the enclosure are assembled a power amplifier, a CD player, and a voltage transformer, thus the acoustic source made in the present work can operate as soon as plugged in. For a noise transfer function test, a random pink noise, of frequency range up to 1024 Hz, and of a long-enough duration time, was synthesized by using Matlab and was recorded on a CD.

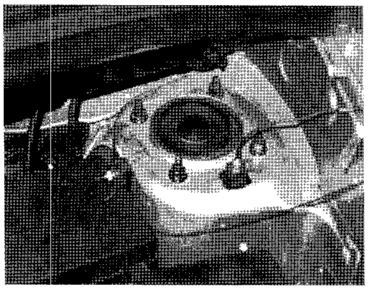

Figure 1. A 3-axis accelerometer mounted on the left front strut mount.

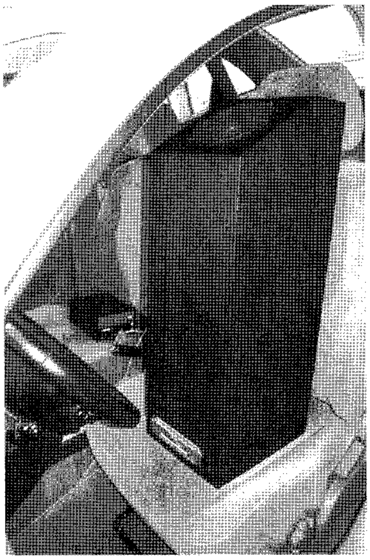

Figure 2. Acoustic volume source for noise transfer function test.

The reference point k, where the reference noise transfer function $H_{ji}(\omega)$ is measured by using impact hammer test, need not to be one of those body-suspension mounts listed in Table 1, but the point should be selected with care so that the point satisfy some conditions. From equation (7), it can be seen that an ideal reference point, within the frequency range of interest, does not have anti-resonances in its acceleration spectrum, and it does not have a poor coherence with the response sound pressure at the loudspeaker position. A good candidate point would have a strong local stiffness. One such point found in the test was a point at the upper portion of the A-pillar as shown in figure 3. A typical acceleration ratio function measured in the test is shown in figure 4. It can be noted that there is no sharp peak that would appear when the reference point has anti-resonances.

To verify the validation of the NTF measurement method proposed in the present work, a few noise transfer functions were obtained both by directly measuring

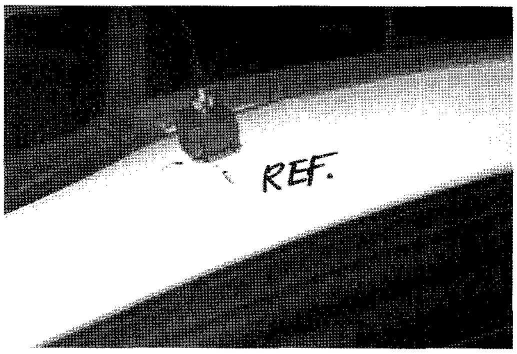

Figure 3. The reference point selected in the test.

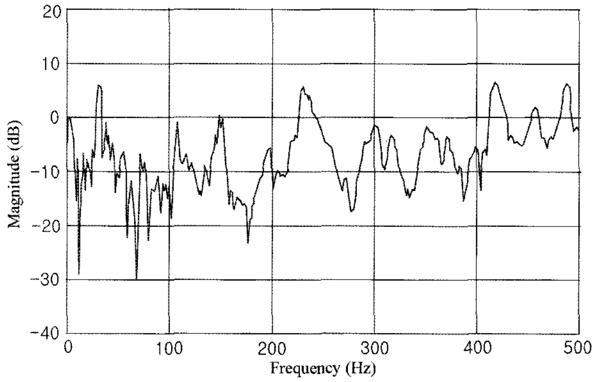

Figure 4. A typical example of acceleration ratio function.

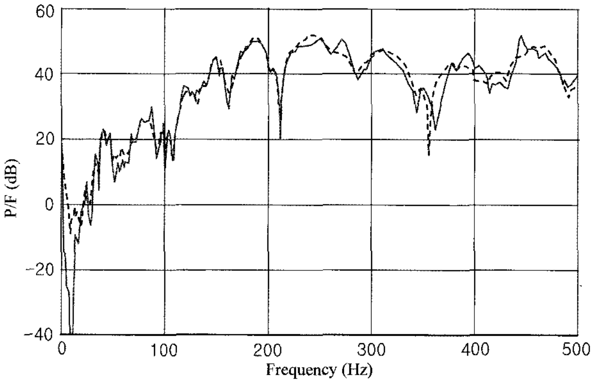

Figure 5. Comparison of the magnitudes of the two different noise transfer function measurement techniques. dashed line: impact hammer test. solid line: proposed reciprocal test. Input path is point 7 in the z-direction, while the receiver point is the driver's ear position.

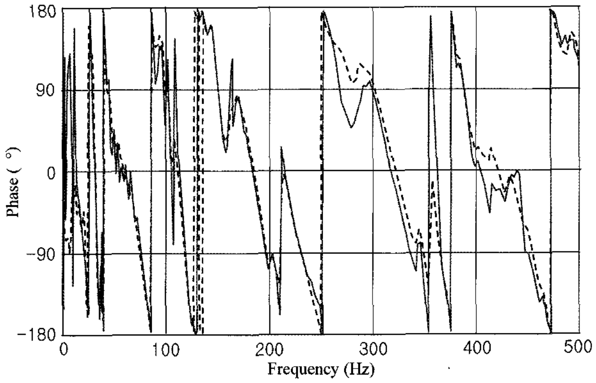

Figure 6. Comparison of the phases of the two different noise transfer function measurement techniques. dashed line: impact hammer test. solid line: proposed reciprocal test. Input path is point 7 in the z-direction, while the receiver point is the driver's ear position.

frequency response functions using impact hammer tests and by processing data from corresponding reciprocal test by using equation (7). The noise transfer functions of the path from z-direction at point 7 (i.e., lower left corner of the front sub frame) to the driver's ear position obtained by the two methods are shown in figure 6 (magnitude comparison) and figure 7 (phase comparison). It can be seen that the noise transfer function obtained by the proposed method is in good agreement with that measured by impact hammer test, both in magnitude and phase. The maximum deviation in magnitude was approximately 5dB in the frequency range from 50 to 350 Hz which cover most of the frequency range of interest for road noise evaluation.

4. CONCLUSION

In the present work, an alternative method that can be used in the noise transfer function measurement was proposed. The new technique is based on the principle of vibro-acoustic reciprocity and has some advantages over impact hammer test.

Some advantages of the technique are that noise transfer functions for input forces in tangential directions at mount positions can be more easily measured, and that that multiple noise transfer functions can be simultaneously obtained by using a multi-channel data acquisition system and multiple three-axis accelerometers for multiple noise transfer paths, thus saving test time.

All the previously proposed measurement methods based on the principle of vibro-acoustic reciprocity have involved the calculation of the volume velocity of the acoustic source, but present technique does not require the calculation of the volume velocity at all. It is shown that once a reference noise transfer function is obtained at an appropriate input path (by using impact hammer test), any volume source can be used and even replaced with a different volume source during the experiment as long as it is placed at the same receiver position. An impact point on the upper portion of the A-pillar was found to be a proper reference point.

To evaluate the road noise of a midsize sedan, the noise sensitivities of the selected body-suspension mount paths were efficiently obtained by using the measurement technique and the easy-to-use volume source devised in the present work, thus verifying the usefulness of the technique in a practical viewpoint.

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