On a Simple Technique to Measure the Airborne Noise in a Motor Vehicle using Source Substitution

C. D. Juis[1], A. Putra[2]

Abstract – *From various methods of measuring noise of a motor vehicle, there is a lack application on how to obtain the 'pure' airborne noise in a vehicle cabin as an important measure to improve the noise control treatment. This project proposes a technique in separating airborne and structure-borne noise in a motor vehicle using sound source substitution method. A cone loudspeaker was used as the substitution source and the overall transmission loss was measured to achieve this purpose. It is found that the structure-borne noise is dominant at low frequencies and airborne noise dominates at high frequency. The intersection frequency between the two is roughly 400 Hz.*

Keywords*: Airborne Noise, Structure-borne Noise, Transmission Loss, Source Substitution*

I.   Introduction

The noise in the passenger compartment of a car has been an issue lately in the automotive engineering. A good quality car is the one that produce low noise and vibration. Noise, vibration and harshness (NVH) of a car becomes an important parameter judged by the customer [1]. Therefore for a car manufacturer, accurate measurement of noise and vibration is necessary.

According to its transmission path, noise can be classified into two categories, i.e. structure borne and airborne noise. The word "borne" means to bear or to carry. Therefore structure-borne is the vibration carried by the structure, where it is then transferred as sound energy which is produced inside a car. Meanwhile, the airborne noise is propagation of noise directly through the air [2].

For noise in the vehicle cabin especially, engineers need to separate between airborne and structure-borne noise as a measure of how well the noise control treatment applied. Airborne noise is transmitted directly into the cabin through gaps and leakage in the car. Meanwhile, for the structure-borne noise, the noise is usually generated by the vibrating car engine, exhaust and other parts. In other words, the noise is generated by vibration at the mounting point. The vibration waves propagate through the vehicle structure of the cabin and then radiate the noise. See Fig. 1.

The noise via the structure-borne route is the coupling between the structural resonance and cabin acoustic modes and hence is typically modal dominating at low frequencies below 500 Hz. As the frequency increases, the interior noise is well dominated via the airborne route particularly due to tyre and wind noise [3]. Therefore, airborne noise corresponds to the sealing for any leakages and the structure-borne corresponds to the applied damping or isolator of the car structures.
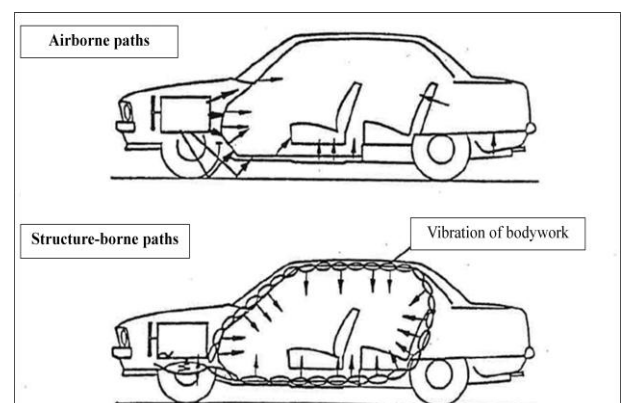

Fig. 1: Transmission paths of airborne and structure-borne noise.

As the sound in the cabin is a mix of airborne and structure-borne noise, a technique

is required to well separate these two types of propagating noise.

Techniques to assess the motor vehicle interior noise are progressively developing. In 1980's, Fahy introduces the sound intensity technique where the sound intensity at any particular radiating surface can be obtained [4]. This requires a scanning process for several surfaces to yield the sound intensity distribution inside the vehicle interior. The signal processing method can also be applied to ranking the sources of noise in the cabin. Several accelerometer and microphones are required to obtain the raw data [5, 6]. The suspected noise sources are ranked by their signal coherencies. The most recent techniques are the implementation of array of microphones using Beam-forming method and Near-field acoustical holography [7, 8, 9]. These provide the measure of 'source strength' distribution from the sources. As for sound intensity, this does not need the scanning process, but requires more than 20 acoustic microphones (and also amplifier and data acquisition system with multiple channels) to obtain a good data. The method becomes more attractive as this can be coupled with video image processing to give a live measurement for the noise source emitting unsteady-state radiation. A powerful algorithm for the signal processing is therefore needed.

This paper presents a simple technique to measure the pure airborne noise level in a car cabin. A cone loudspeaker is used as the source substitution to obtain the overall transmission loss. The methodology is briefly explained in the next section.

II. Methodology

II.1. Exterior noise

The experiments are basically divided into two parts, where first is to measure the exterior noise and second is to measure the interior noise. Each of it using either the engine of the car under test as the noise source or using the source substitution, which is a small 80 Watt cone loudspeaker.
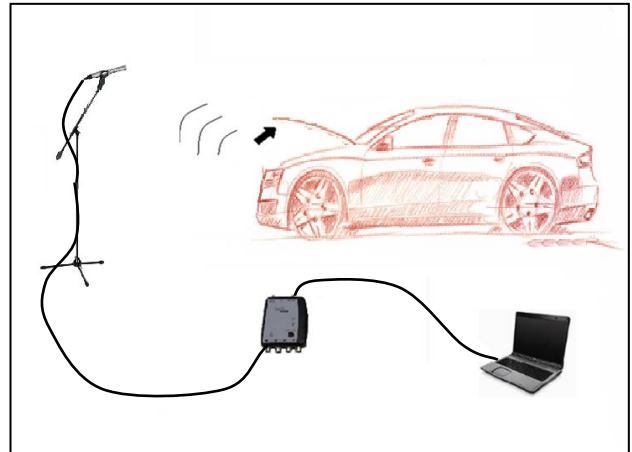

Fig. 2: Experimental setup for exterior noise

Fig. 2 shows the experiment setup to obtain the sound pressure level (SPL) of the exterior noise. The aim is to measure the 'source strength' from the car engine. For this purpose, the bonnet was opened. The microphone was located about 1 m from the engine. The engine was then turned on with idle condition. The acoustic pressure was measured by the ½" GRASS microphone. The signal was captured by the Pro-Photon+ analyzer and transferred into the computer for post processing. The same procedure was then repeated for engine with 2000 rpm, 3000 rpm and 4000 rpm.

When using the source substitution, the loudspeaker was located near the engine facing upwards as seen in Fig. 3 and the engine was turned off. The same procedure was used until the data was saved in the computer.

Fig. 3: Position of the loudspeaker as the substitution source to obtain exterior SPL.

II.2. Interior noise

Fig. 4 shows the experiment setup to obtain the SPL of the interior noise. The microphone was now located in the cabin at the driver's ear position as shown in Fig. 5. The procedures were the same as in the exterior noise measurement, but with the car bonnet now closed. The loudspeaker was also placed near the engine and was now facing towards the cabin.
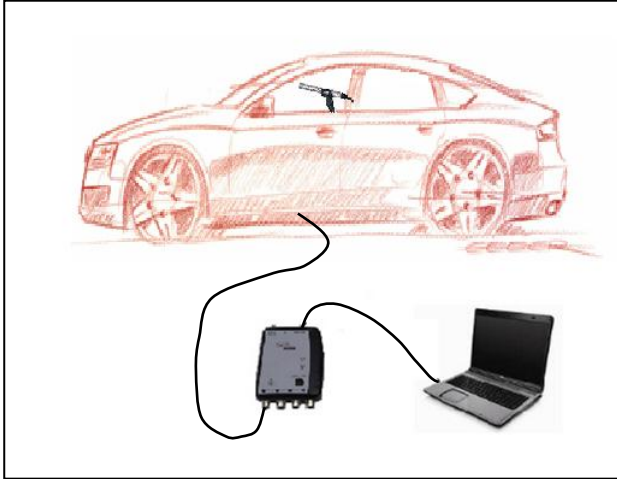

Fig. 4: Experimental setup for interior noise.

Fig. 5: Position of the microphone to measure interior SPL.

III. Data processing

The formula to obtain the sound pressure level during the experiment is given by

$$SPL = 10\log_{10}\left(\frac{|p|^2}{p_o^2}\right) \qquad (1)$$

where p is the acoustic pressure measured by the microphone and p_o is the reference sound

pressure, i.e. 2×10^{-5} Pa. For a propagating plane wave, the sound pressure W is given by

$$W = \frac{|p|^2}{\rho c} \qquad (2)$$

where ρ is the density of air, c is the speed of sound and A is the area of propagation. As the transmission loss is the difference between sound power level ($10\log_{10}W$) of the incident sound and the transmitted sound, therefore according to Eqs. (1) and (2), the transmission loss can also be expressed as the difference between the sound pressure level of measured from exterior and that from the interior. This can be written as

$$TL = SPL_{ext}^{ss} - SPL_{int}^{ss} \qquad (3)$$

where SPL_{ext}^{ss} is the sound pressure level at the exterior and SPL_{int}^{ss} is the sound pressure level at the car interior. Both are those measured using the source substitution.

This transmission loss shows the 'transfer function' of the barrier (wall structure of the car) between the engine as the noise source and the car cabin as the room receiver. As the transfer function is independent of the strength of the noise source, therefore by using the measured source strength, i.e. the exterior SPL when engine is on, the sound pressure level inside the cabin due to 'only' the airborne noise can be obtained. This is expressed as

$$SPL_{airborne} = SPL_{ext}^{en} - TL \qquad (4)$$

where SPL_{ext}^{en} is the sound pressure level measured at the exterior when the engine is running on idle mode, 2000 rpm, 3000 rpm or 4000 rpm.

IV. Result & Analysis

Fig. 6 shows the measurement data of the SPL at the exterior and interior of the car cabin when the engine is running on 2000 RPM. It can be seen that the total SPL at the interior of the cabin becomes much lower than that of the exterior above 500 Hz. This shows the

effectiveness of the car body starting at 500 Hz to block the noise through the airborne. The control measure such as the trimming of the car wall or a double-panel installation of the bulkhead are affecting significantly for the attenuation above this frequency. However, below 500 Hz, the interior SPL is higher than that of the exterior due to contribution of the structure-borne noise. In these low frequencies, the interior noise dominates by the acoustic cavity modes indicated by the distinct sharp peaks. The results for idle mode, 3000 rpm and 4000 rpm show the same phenomenon.
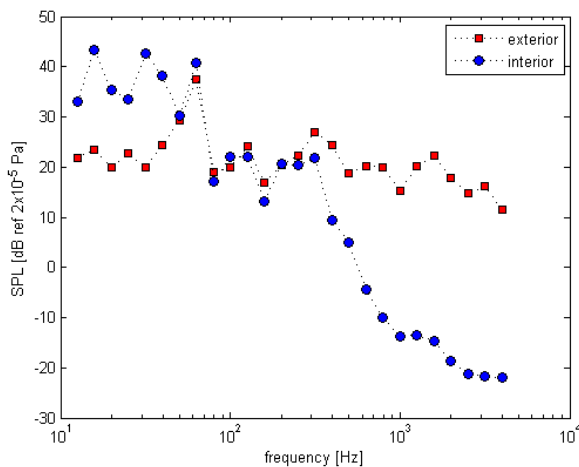

Fig. 6: Measured SPL when the engine is running at 2000 rpm

Fig. 7 shows the SPL measured when the loudspeaker is used as sound source substitution. The SPL inside the cabin is lower compared with that from the exterior for the whole frequency range. The difference increases as the frequency increases.
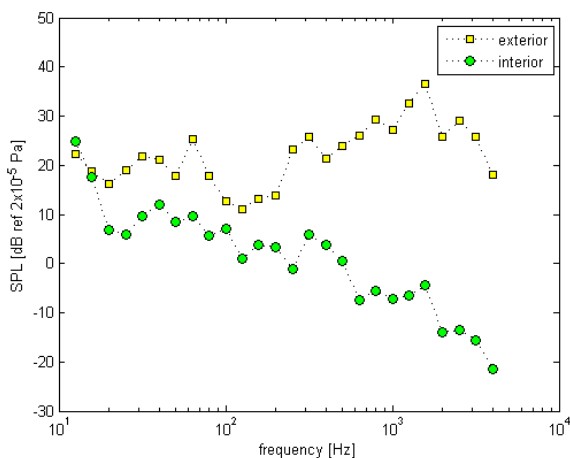

Fig. 7: Measured SPL using the source substitution.

The phenomenon below 500 Hz as in Fig. 6 vanishes as only airborne noise was generated.

Fig. 8 shows the transmission loss calculated from SPL in Fig. 7 (Eq.(3)). It shows that the measured data follows the slope of the 'mass-law', i.e. 20 dB per decade.
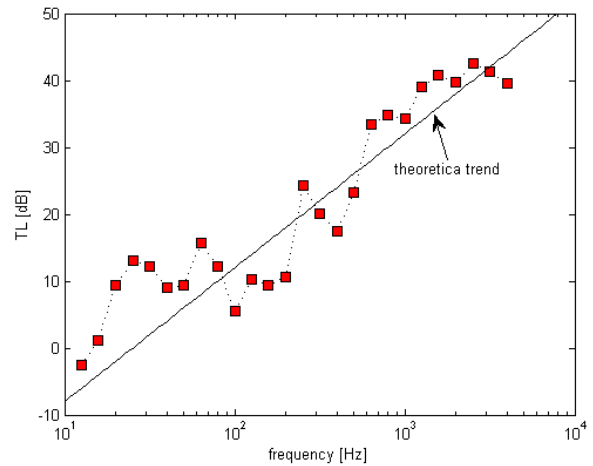

Fig. 8: Measured sound transmission loss.

The results for the airborne noise in comparison with the total interior noise are shown in Fig. 9 -12.

From all the figures, the airborne noise and structure-borne noise start to converge roughly above 400 Hz. In Figure 9 for the idle condition however, the difference between the total and the airborne SPL is around 15 dB. This is because the airborne penetrates the cabin with less amount of energy compared with other engine's rpm.
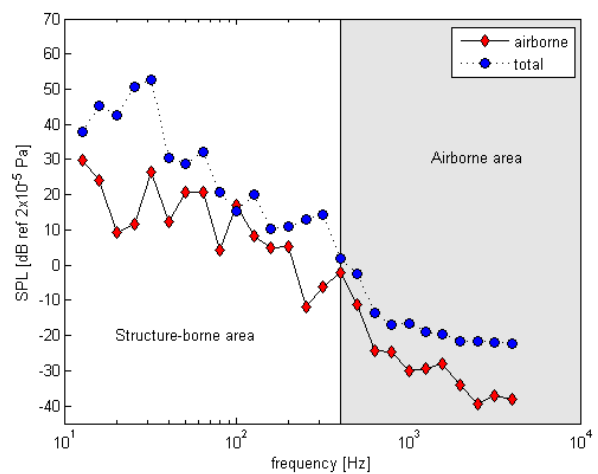

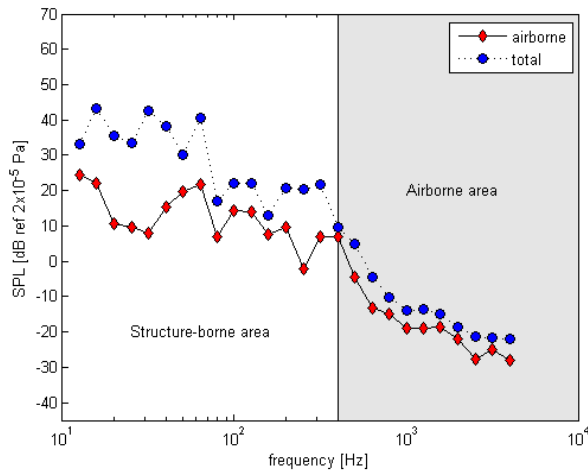Fig. 9: Total SPL and airborne SPL at idle.

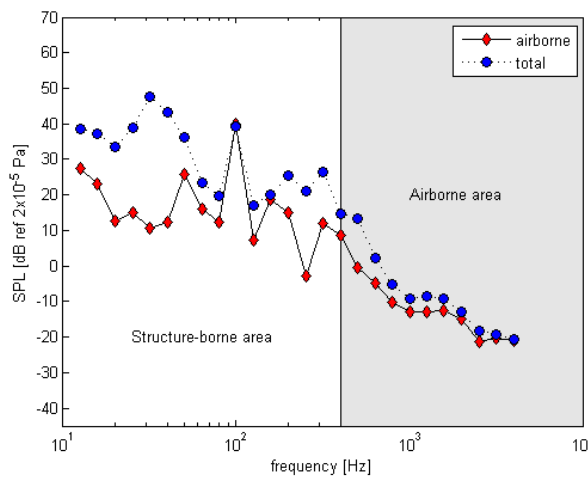Fig. 10: Total SPL and airborne SPL at 2000 rpm.

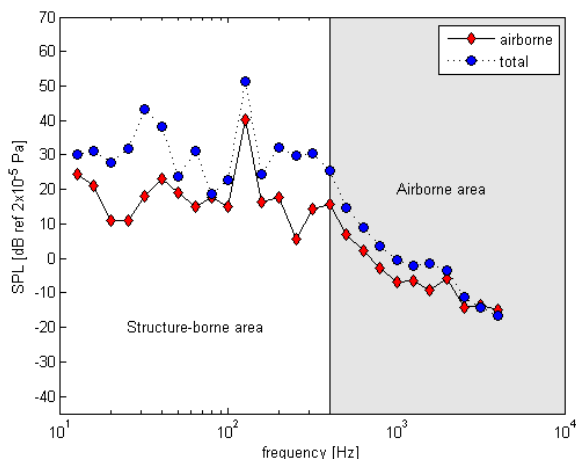
Fig. 11: Total SPL and airborne SPL at 3000 rpm.

Fig. 12: Total SPL and airborne SPL at 4000 rpm.

From this phenomenon, it can be concluded that the total SPL above 400 Hz dominates by predominantly by the airborne noise, while the structure-borne noise can be seen to dominate below 400 Hz where the total SPL is higher than that of the airborne noise of about 10 – 20 dB.

A sharp peak in the structure-borne frequency range shows the second order of the engine harmonic, $2E$ where E is the frequency of the running speed of the engine. For example a peak seen at 100 Hz when the engine is running at 3000 RPM (Figure 12) is due to the engine harmonic, $2(3000/60) = 100$ Hz. The same peaks can be seen at 30 Hz, 65 Hz and 130 Hz in Fig. 9, 11 and 12, respectively for other engine's rpm.

It is also interesting to note, that the SPL for different engine's rpm are roughly the same at the structure-borne area. The SPL increases as with the increasing of rpm only at the airborne area. This shows that the engine speed contributes significantly for the broadband of airborne noise inside the cabin. At low frequencies, the contribution is only due to the engine orders at distinct frequencies.

V. Conclusion

A method to measure the airborne noise in a motor vehicle has been proposed using source substitution method. The pure airborne sound pressure level inside the cabin can be obtained when the engine is running on several speeds. It is found that the intersection frequency between the structure-borne noise and the airborne noise is around 400 Hz. This transition frequency is also found to be independent of the speed of the engine.

In the experiment, a small cone loudspeaker having power of 80 Watts was used as the source substitution. However, for more accurate results to measure the airborne noise, it is better to use sound source producing larger sound energy particularly at high frequencies to penetrate the vehicle cabin optimally.

References

[1] K. Genuit. The sound quality of vehicle interior noise: a challenge for NVH-engineers. *Int. J. Vehicle Noise and Vibration*, Vol. 1, 2004.

[2] M. Harrison. *Vehicle Refinement: Controlling Noise & Vibration in Road Vehicle*. 1st Ed. Burlington, MA.: Elsevier Butterworth-Heinemann, 2004.

[3] D. J. Thompson and J. Dixon. Vehicle noise. Chapter 6 in *Advanced in Acoustics, Noise and Vibration* (Ed by F. Fahy and J. Walker), Spon Press, 2004.

[4] F. J. Fahy. *Sound Intensity*. 2nd Ed, E & FN Spon, 1995.

[5] W. G. Halvorsen and J.S. Bendat, Noise Source Identification using Coherent Output Power Spectra, *Journal of Sound and Vibration*, pp. 15–24, 1975.

[6] H. Fouladi, J. M. Nor and A. K. Arifin. Spectral analysis methods for vehicle interior vibro-acoustics identification, *Mechanical Systems and Signal Processing,* Vol. 23, pp. 489– 500, 2009.

[7] M.G. Smith, K.B. F Kim and D.J. Thompson. Noise source identification using microphone array, *Proceeding of the Institute of Acoustic*, Vol 29.Pt.5, 2007.

[8] P. A. Nelson. and S.H. Yoon. Estimation of acoustic source strength by inverse methods: Part I: Conditioning of the inverse problem. *Journal of Sound and Vibration*, 233, 643–668, 2000.

[9] F. Jacobsen and V. Jaud. Statistically optimized near field acoustic holography using an array of pressure-velocity probes. *Journal of the Acoustical Society of America,* 131(3), 1550-1558, 2007.

Clinton Dale Juis was born in Kuching, Sarawak on 13th June 1985. He received Certificate (2005) and Diploma (2007) of Mechanical Engineering from Polytechnic. He is now the final year student pursuing Bachelor of Mechanical Engineering (2011) majoring in Structure and Materials in Universiti Teknikal Malaysia Melaka (UTeM).

Azma Putra is a senior lecturer in Faculty of Mechanical Engineering, UTeM. He received his Ph.D in 2008 from Institute of Sound and Vibration Research (ISVR), University of Southampton, United Kingdom. His current interests are engineering acoustics and noise control, vibro-acoutics, vibration and structural dynamics.