MEASUREMENT OF STRUCTURE-BORNE NOISE FROM ROAD INPUT IN A MOTOR VEHICLE CABIN

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Abstract

Vehicle interior noise has been an important aspect to determine quality of a vehicle since it affects the level of acoustic comfort of the passengers. This paper proposes a simple noise measurement technique to quantify the contribution of the structure-borne noise due to tire-road interactions. A subcompact sedan was used as the test vehicle in this study. The Sound Pressure Level (SPL) inside the cabin was measured in two conditions – i) laboratory test when the test vehicle was running on a dynamometer and ii) field measurement. In the laboratory measurement, the SPL was measured at the engine speed of 1000, 2000, 3000 and 4000 revolutions per minutes (RPM). In the field measurement, the SPL was measured when the test vehicle was running at a steady RPM and the vehicle speed in the range of 60 to120 km/hr. The results showed that there was a profound contribution of structure-borne noise from the tire-road interaction and aerodynamic excitation at frequency below 400 Hz. It can be concluded that the structure noise-born in a vehicle is possibly contributed from road input interaction, vehicle suspension system and aerodynamic excitation on the vehicle.

Keywords: Airborne noise, Interior noise, Sound pressure level, Source substitution, Structure-borne noise, Tyre noise

Introduction

Vehicle interior noise has attracted attention from researchers and manufacturers since the past decades as it crucially affects the level of acoustic comfort of the passengers. Noise from the engine has so far been successfully controlled with the production of low-noise engine, especially for luxury sedans. Sound insulation treatment has also been shown to be an effective method to reduce noise transmitted into the passenger compartment, especially for high frequency sound. However, noise from tires still gives a challenging problem, as the noise source, i.e. the tire and road interaction is difficult to control and as the noise dominates mainly in the low frequency region.

Generally, this vehicle interior noise due to tires is classified into two types of detectable noise, namely structure-borne and airborne noise. The structure-borne noise is generated, for example when tires travel on a non-uniform road surface which causes structural excitation through the tires and suspension system into the vehicle body. This structural excitation then generates noise radiated into the cabin. The excessive bending modes from the front suspensions are one of significant sources of structure-borne noise [1]. The noise produced by the tire-road interaction had become the most important source of vehicle noise for driving speeds above 40 km/hr [2]. Meanwhile, the airborne noise is the noise radiated directly from the tires-road interaction, engine and exhaust which is transmitted into the cabin through leakages due to lack of door and window sealing [3]. Figure 1 shows a chart illustrating the structure-borne and airborne noise [4].

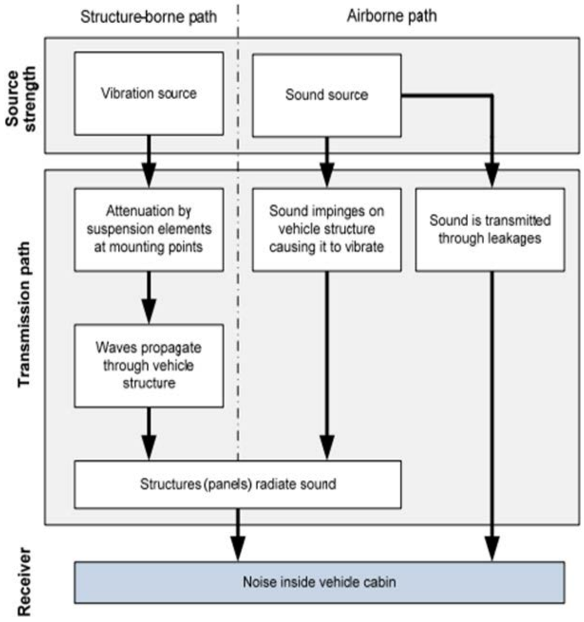

Figure 1. Vehicle interior noise transmission path [4]

Techniques to measure the vehicle interior noise are progressively developing. Kim et al. [5] measured the structure-borne noise transfer paths by using an emulated vehicle system ranging from 100 Hz to 2.8 kHz. They successfully investigated the path rank ordering schemes based on partial sound pressure. Kindt et al. [6] conducted an experimental analysis of induced structure-borne tire-road interaction to analyse the peak noise levels as a result of driving across road discontinuities. Experimental study of the friction-induced noise generated by the vehicle’s brake system had been conducted by Lindberg et al. [7]. Liu et al. [8] performed interior noise analysis by using the SYSNOISE for the vehicle model which is first constructed and simulated by using ADAMS and MSC/NASTRAN software. Mohanty et al. [9] also performed numerical techniques to predict the structure-borne noise in a truck cab. In the simulation, a panel acoustic contribution analysis (PACA) technique was used to determine the structural areas of the cab which contributes to most of the interior noise level. Junoh et al. [10] performed noise measurement to determine the amount of interior vehicle noise which was influenced by the vibration due to interaction between tires and road surface. The tests were conducted for different road profiles.

This paper proposes a method to measure the structure-borne noise in a motor vehicle cabin due to road input. This is combined with the established technique from Putra et al. [4] to measure the contribution of the airborne noise from the engine and therefore separates the region of the structure-borne noise from the total noise in the vehicle cabin.

Methodology

This study consists of three parts –i) airborne noise measurement by using the substitution source, ii) noise measurement when test vehicle is running on the road and iii) noise measurement when test vehicle is running on a dynamometer. For all the measurements, sound level meter (SLM) RION Na-28 was used (Figure 2). The acoustic microphone was first calibrated using RION calibrator NC-74 and the sound pressure level (SPL) was recorded in one-third octave bands. In the cabin, the SLM was located at the driver’s ear position as shown in Figure 2. British Standard BS 6086-1981 (ISO 5128-1980) [11] is followed closely throughout this study.

Figure 2. Location of the sound level meter (SLM) at the driver's ear position

Airbone Noise Measurement by Using Substitution Method

The experiments were divided into two parts – i) the exterior noise and ii) vehicle interior noise measurements. For the exterior noise measurement, the vehicle bonnet was opened in order to obtain the source strength from the engine noise and the noise was measured by using the sound level meter. The engine is turned on and was set to run at 1000 rpm. The same procedure was then repeated for engine running at 2000 rpm, 3000 rpm and 4000 rpm.

The exterior noise measurement was continued with the substitution method. This substitution method was used to obtain the airborne transfer function for the vehicle. A loudspeaker rated at 60 Watt facing outwards the bonnet was used in this experiment to give the “white noise” (Figure 3).

As for vehicle interior noise measurement, the engine noise was measured inside the car at the driver’s position by using the SLM, but this time with the car bonnet closed. The interior noise is recorded for the engine running at 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm.

The same procedure was continued for the substitution source with loudspeaker was facing towards the car's bulkhead and with the bonnet closed. From all these data, the airborne noise can be extracted. Details of the signal processing and the calculation can be referred in Putra et al. [4].

Interior Noise Measurement from the Road and Dynamometer Input

Both the noise measurement from the road and dynamometer input was conducted for 10 seconds at engine speed of 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm. In the case of noise measurement from road input, the noise measurement was only started when the vehicle was running at steady RPM and the velocity of the vehicle was in the range of 60-120 km/h with the transmission in the highest position without exceeding 120 km/h as per described in BS 6086-1981 (ISO 5128-1980) [11].

The route chosen for this experiment was of a common road roughness as in most roads in the city where the experiment was conducted on the same route for each noise measurement. The driver's driving pattern was constant throughout the whole experiment.

The same procedures were repeated for the noise measurement from dynamometer input. All sources of background noise were avoided during the experiment was conducted i.e. exhaust fans, air conditioning in test vehicle (turned off). Figure 4 shows the noise measurement setup when vehicle was running on dynamometer.

All the recorded SPL were transferred into computer for post-processing using Matlab.

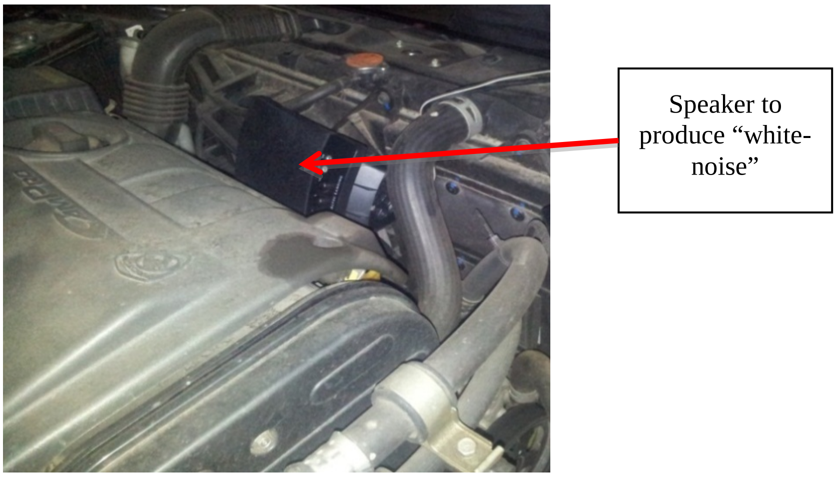
Speaker to produce "white-noise"

Figure 3. Location of the loudspeaker for exterior noise measurement using substitution source

Figure 4. Test vehicle running on dynamomete

Results and Discussion

Figures 5 to 8 show the measurement data of the exterior and interior SPL of the car when the engine was running at 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm. These measured SPL was in one-third octane band and is the mixture of airborne and structure-borne noise.

It can be seen that the same phenomenon occurs for each engine speed which is the interior SPL starts to decrease steadily at frequency above 400 Hz. At frequency below 400 Hz, the interior SPL measured has the similar value with the exterior SPL. The interior SPL increased steadily for frequency below 400 Hz, and started to decrease gradually as the frequency increase above 400 Hz. Higher interior SPL at low frequency is due to the contribution of the structure-borne noise from the engine. At frequency above 400 Hz, the interior SPL starts to decrease steadily while on the other hand, the exterior SPL increases steadily.

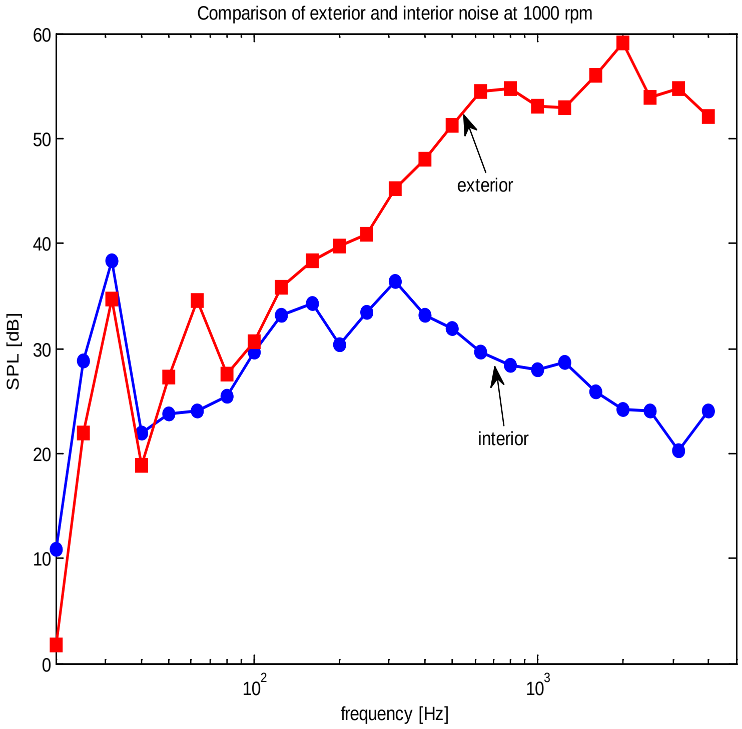

Figure 5. Measured SPL when engine is running at 1000 rpm

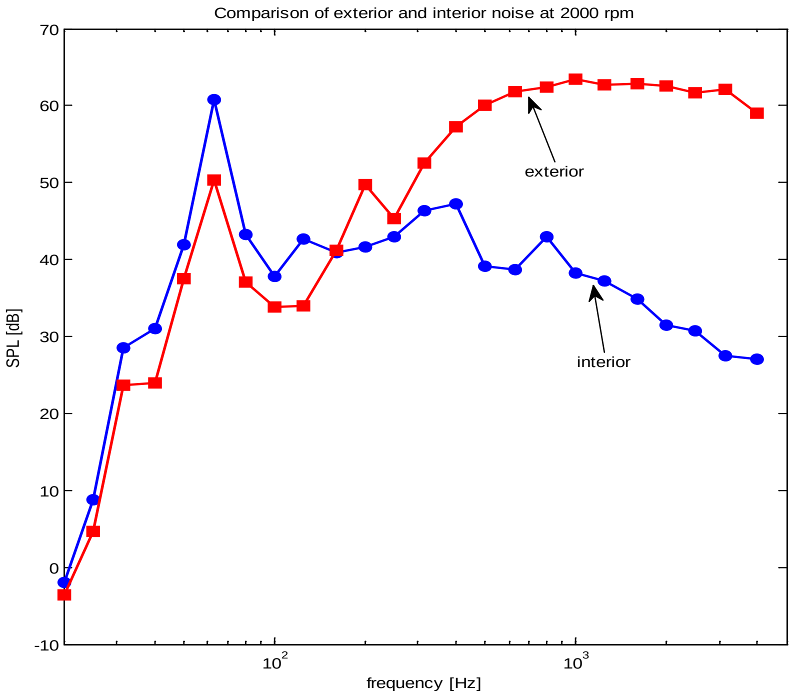

Figure 6. Measured SPL when engine is running at 2000 rpm

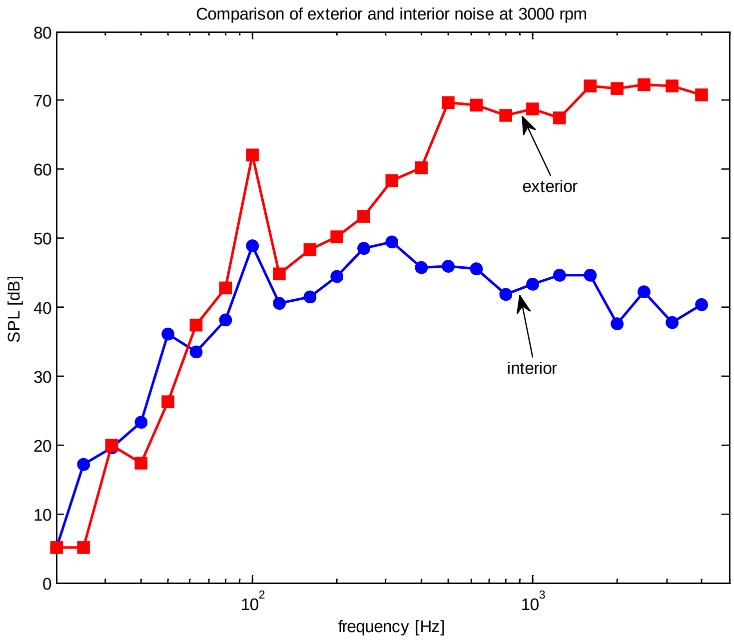

Figure 7. Measured SPL when engine is running at 3000 rpm

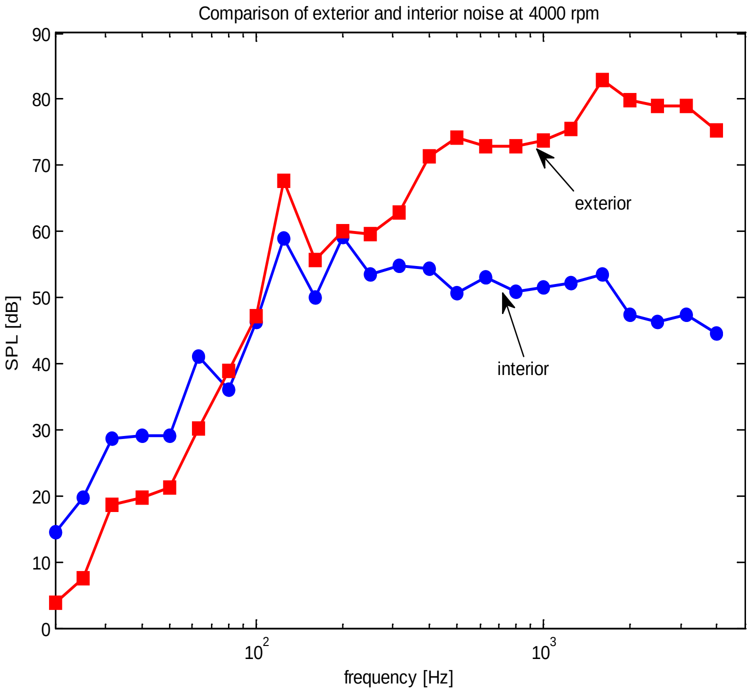

Figure 8. Measured SPL when engine is running at 4000 rpm

Figure 9 plots the SPL measured at interior and exterior of the vehicle by using loudspeaker as the substitution source. The exterior SPL measured is higher compared to the SPL measured inside the vehicle cabin for the entire frequency range. The interior SPL increases gradually at frequency below 400 Hz and then became constant at frequency above 400 Hz. The SPL difference between exterior and interior increases as the frequency increases.

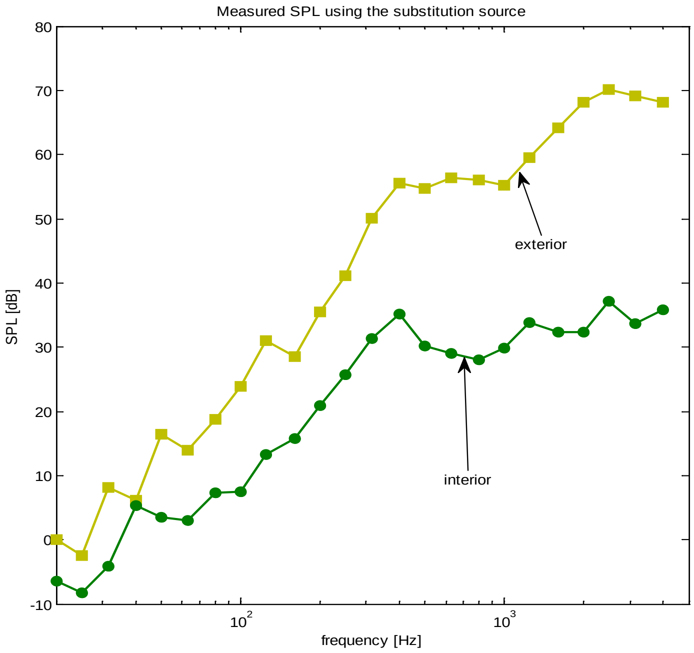

Figure 9. Measured SPL using the substitution source

Figures 10 to 13 show the comparison of total interior noise and airborne noise when engine is running at 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm. At 1000 rpm, it is notable that at frequency above 400 Hz, the airborne noise and total interior noise start to converge as the frequency increases. This result shows that at frequency above 400 Hz, the total interior noise of vehicle cabin is predominantly airborne noise due to the engine vibration since. At frequency lower than 400 Hz, the SPL difference between total interior noise and airborne noise is the structure-borne noise. The results for 2000 rpm, 3000 rpm and 4000 rpm show the same phenomenon.

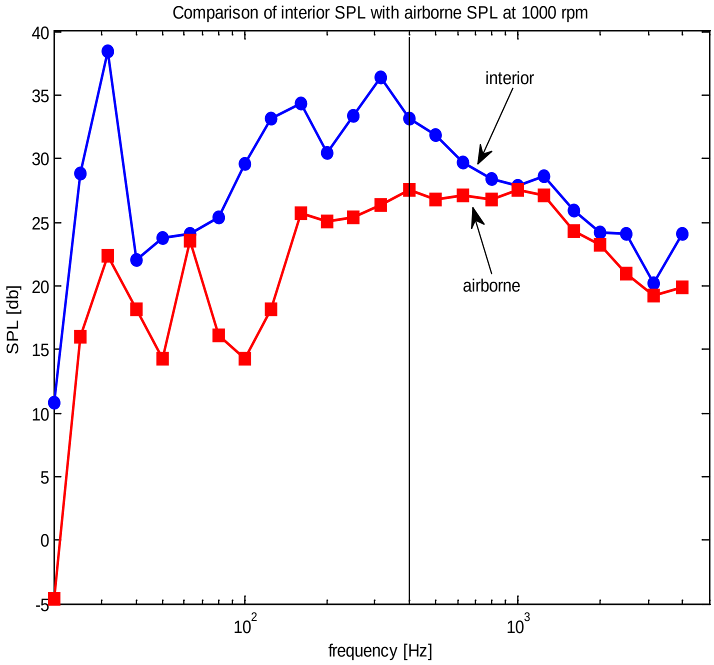

Figure 10. Comparison of interior SPL with airborne SPL at 1000 rpm

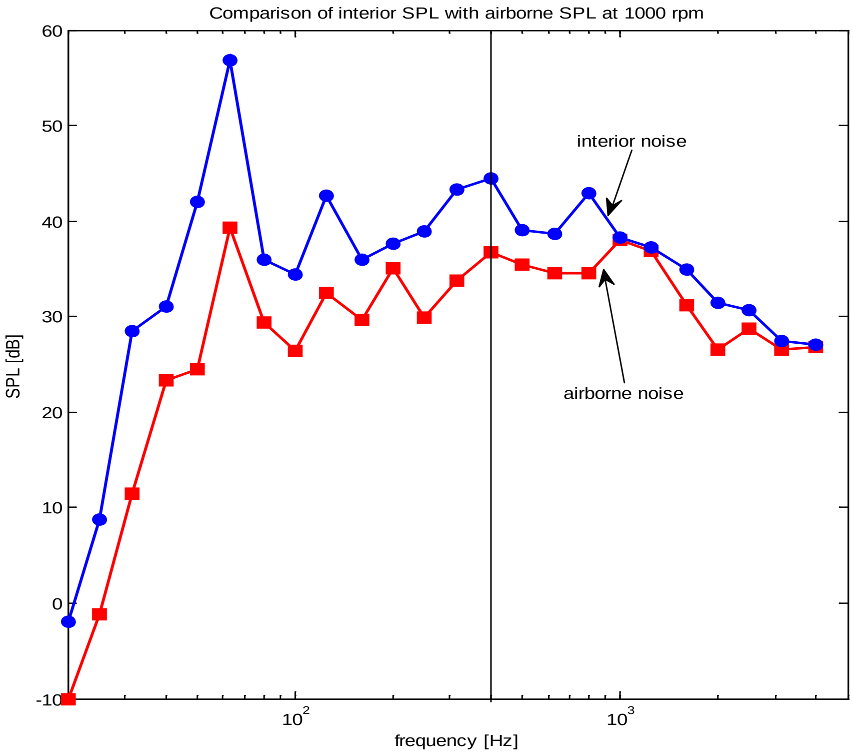

Figure 11. Comparison of interior SPL with airborne SPL at 2000 rpm

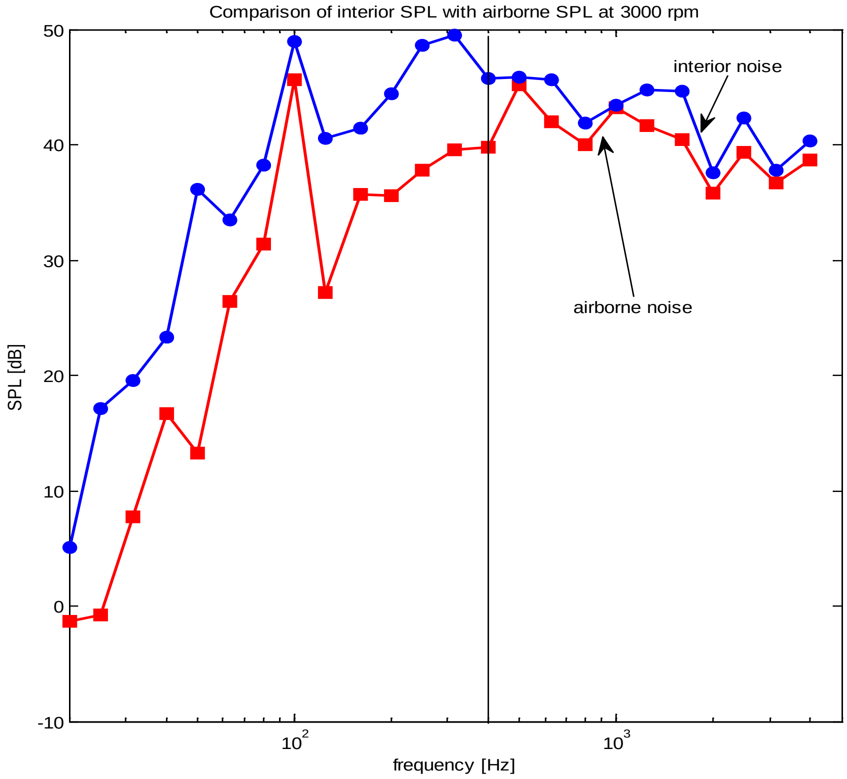

Figure 12. Comparison of interior SPL with airborne SPL at 3000 rpm

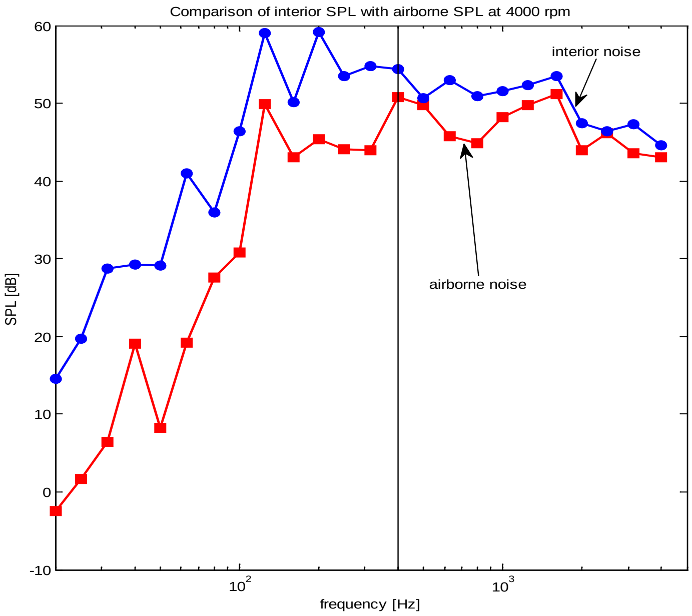

Figure 13. Comparison of interior SPL with airborne SPL at 4000 rpm

Figures 14 to 17 plot the combined SPL at engine speed of 1000 rpm, 2000 rpm, 3000 rpm and 4000 rpm. All the figures clearly show significant SPL difference between dynamometer input and road input which is the contribution of structure-borne noise due to road-tire interactions, vehicle suspension and aerodynamic effect on the vehicle body at frequency below 400 Hz. As the engine speed increases (vehicle velocity increases) the contribution of structure-borne noise due to road input increased by around 3 – 5 dB.

The structure-borne noise contributed by the aerodynamic excitation on the car is known as ‘greenhouse surfaces’. This aerodynamic caused structure-radiated noise at the glasswork and the roof panel and then transmitted into vehicle interior through structure-borne route [3]. Nevertheless, there is dominant noise generation mechanism for tire below 1 kHz is the tire wall vibration caused by the collision between the tread blocks and the road causes [5].

Most of the road induced structure-borne noise below 600 Hz is related to the dynamic characteristic of suspension system [12]. Vibration induced when vehicle crossing road irregularities is transmitted into vehicle cabin thru vehicle suspension and other mounting parts. Most of the road induced structure-borne noise below 600 Hz is related to the dynamic characteristic of suspension system. Vibration induced when vehicle crossing road irregularities is transmitted into vehicle cabin thru vehicle suspension and other mounting parts [13].

A distinct peak at all measured SPL at low frequencies shows the contribution of structure-borne noise due to second order engine harmonic, 2E where E is the frequency of the running speed of the engine. For instance a peak seen at 66.67 Hz when the engine is running at 2000 rpm (Figure 15) is due to the engine harmonic, 2(2000/60) = 66.67 Hz. The same peaks can be seen at 33.33 Hz, 100 Hz and 133.33 Hz for respective engine’s speed as show in Figures 14 to 17.

It is also notable that at frequency above 400 Hz, there is a slight difference roughly around 2 dB – 3 dB between the SPL measured when vehicle is running on the road and dynamometer. This SPL difference is due to the contribution of airborne noise from airborne tire noise, engine airborne noise and aerodynamic noise into the vehicle cabin.

Furthermore, there is also noise contribution from tire-road interaction that is transmitted into vehicle cabin through airborne route. Airborne tire noise is generated when air is pumped in and out of tire tread and road irregularities during the contact [14]. The area of contact of the tire and the road surface form a horn-like geometry which provides a significant amplification mechanism. As a result (see Figure 16), this amplification generates an increase in noise level of about 10 dB – 20 dB at around 1000 Hz in the case of engine speed at 3000 rpm [6].

Structure-borne induced vibration due to road irregularities which generate sudden shock impact to the tires is spread to the rim, suspension, mounting points and other parts of the vehicle body [15].

Airborne aerodynamic noise is another major noise contribution in vehicle cabin. As vehicle move at high velocity, the airflow underside the vehicle causing transmission of airborne noise, particularly in the wheel-ach areas into vehicle cabin [3]. According to Nilsson [16], a high frequency at about 1000-2000 Hz tone bust is generated as the groove of the tire releases from the road contact, thus transmitting noise into vehicle cabin through airborne route. There is also possibility in which the airflow noise from the engine, tire-road interaction and aerodynamic effect that transmitted into interior cabin through seal leakage at the doors and windows.

It can be seen that when the engine is running at 4000 rpm, the measured SPL for road input, dynamometer input, total interior SPL and airborne SPL diverged and collapsed together as the frequency increases. This is because of the rapid increment of interior and airborne noise (stationary) and very slow increment of measured SPL for road and dynamometer input.

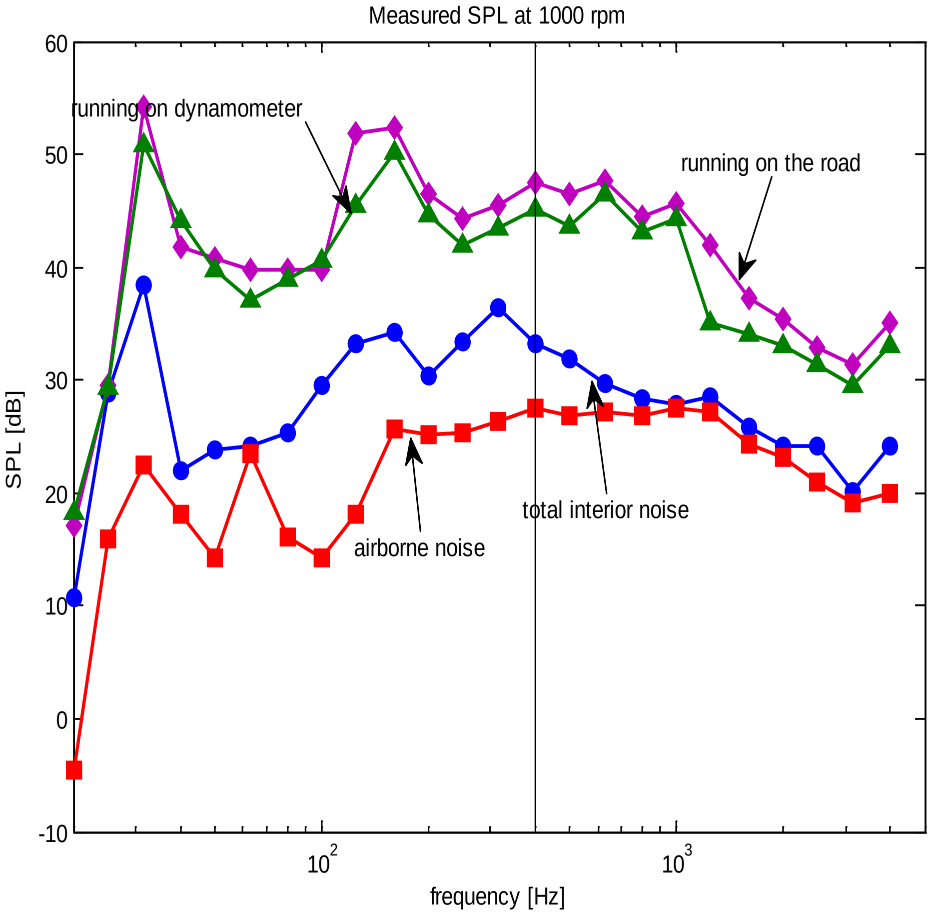

Figure 14. Combined SPL (stationary and running on road + on dynamometer) at 1000 rpm

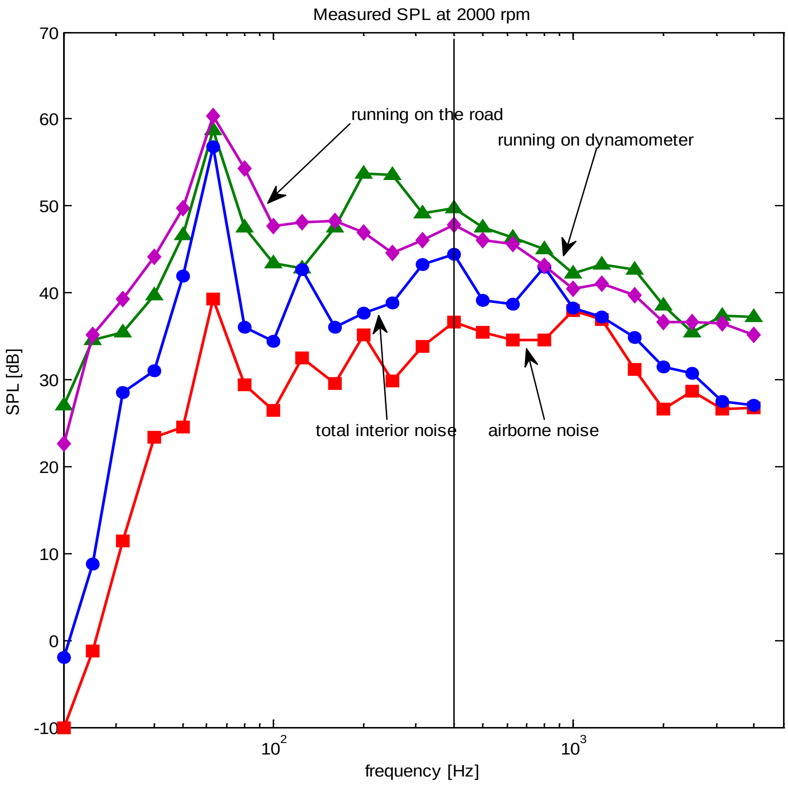

Figure 15. Combined SPL (stationary and running on road + on dynamometer) at 2000 rpm

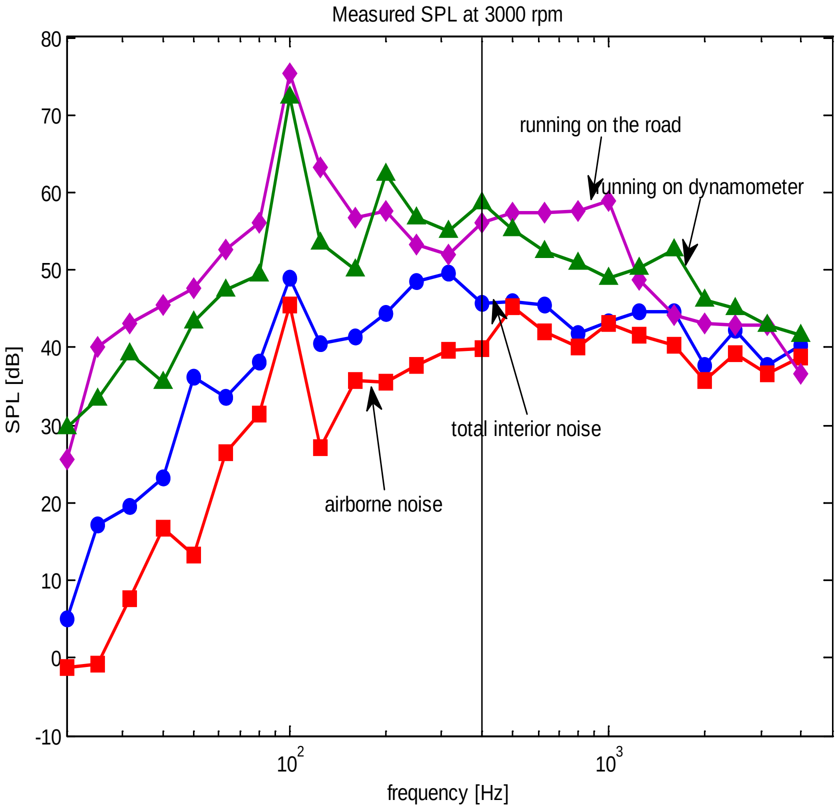

Figure 16. Combined SPL (stationary and running on road + on dynamometer) at 3000 rpm

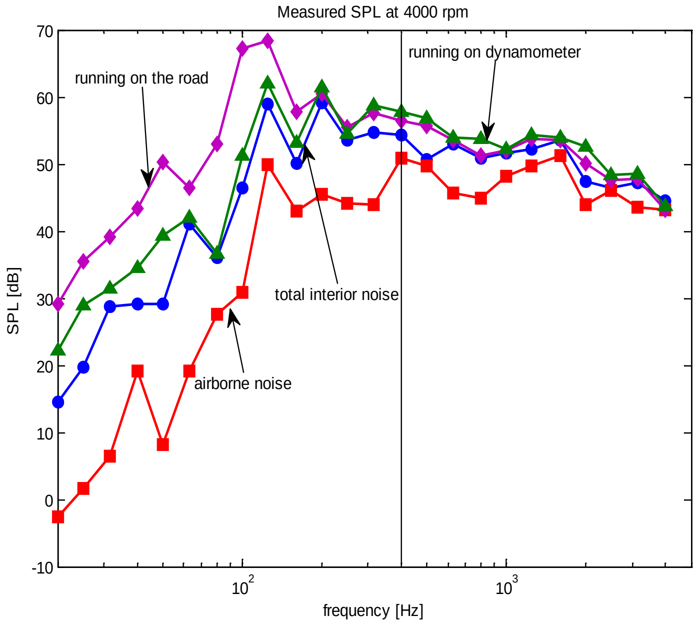

Figure 17. Combined SPL (stationary and running on road + on dynamometer) at 4000 rpm

Conclusions

The comparison between the measured SPL when test vehicle was running on the road and the measured SPL when test vehicle was running on dynamometer showed the contribution of structure-borne noise from the tire-road interaction and aerodynamic excitation at frequency below 400 Hz. The comparison between measured SPL for total interior noise (at stationary condition) and SPL for road input showed the contribution of noise from road input, vehicle suspension system and aerodynamic excitation. In the case of substitution method, vehicle interior noise was dominated by airborne noise at frequency above 400 Hz. It is suggested to conduct the noise measurement in anechoic chamber to avoid background noise disturbance.

It is also advisable to employ ordinary loudspeaker without sound enhancement i.e. bass, treble and equalizer to maintain the original sound characteristic of “white noise”. Also the contribution of noise from vehicle suspension system can be easily identified in this experiment if the dynamometer has the capability to roll accordingly to vehicle engine speed with vehicle engine off during the noise measurement.

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