Sound Power Measurement of Tyre/Road Noise Using the Close-Proximity (CPX) Trailer Enclosure

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ABSTRACT

The present paper reports a new methodology for measuring the sound power level (SWL) of tyre/road noise, using a modified Close-Proximity (CPX) trailer enclosure. Specially designed diffuser panels are implemented to cover the absorption materials on the interior walls and ceiling of the CPX enclosure to create a reverberant chamber. Through numerical simulations, the optimal reverberant chamber design, which holds the least acoustic resonance and most uniform acoustic energy distribution, is determined to guide fabrication. The SWL of a reference sound source (RSS) is determined first. The sound pressure level (SPL) distributions inside the reverberant chamber with the RSS switched on are then obtained under static conditions and road tests. The relationships between the SWL of the RSS and the SPL it produces inside reverberant chamber with various RSS inputs signals show great consistency with theory. Using the linear regression of SWL with respect to spatially averaged SPL reverberant chamber obtained in static condition, the total SWL and its spectrum at a specific vehicle speed can be deduced from the captured SPL information inside the chamber during road tests with the RSS switched off.

1. INTRODUCTION

Traffic noise is receiving increased attention in highly urbanized cities like Hong Kong due to its wide-ranging adverse effects on health, society, and the economy [1-4]. Tyre/road noise dominates traffic noise generation from road networks when passenger cars exceed 50 km/h and heavy vehicles exceed 70 km/h [5]. With the growing popularity of electric vehicles, tyre/road noise is becoming the dominant source of traffic noise pollution in urban areas regardless of vehicle speed.

The Close-Proximity (CPX) method is widely used for tyre/road noise measurement, and its stipulations and recommendations are described in the ISO 11819-2 standard [6]. In this method, test tyres are covered by an anechoic enclosure to shield noise generated from the towing vehicle and prevent contamination from surrounding traffic. Sound absorption materials are laid on the interior walls of enclosure to minimize noise reflections and ensure that tyre/road noise propagates like it would in an open area with no enclosures. The CPX measurement method typically captures only the acoustic pressure generated by tyre/road interactions, and few methodologies have been proposed for sound power level (*SWL*) measurement of tyre/road noise in last few decades. Some studies have used laboratory drum tests [7] and Coast-By tests on the roadside [8] to measure *SWL*. However, the noise generated by tyres rolling against drum segments is different from noise generated by rolling over

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flat road surfaces, and the drum noise can significantly contaminate sound power measurements. Meanwhile, the Coast-By method does not allow for clear differentiation of noise from other sources, such as wind, engine, exhaust system, and vehicle suspension vibration.

Given these limitations, Campillo-Davo et al. [9] proposed an alternative CPX measurement method in which more microphones were added on an extended frame, along with the mandatory microphones specified in the ISO 11819-2 standard [6]. The frame was designed specifically to be fixed on the vehicle body, ensuring that all microphones were fixed on a quarter spherical surface directing the tyre/road contact patch to capture incident noise levels as the tyre rolls. The *SWL* of tyre/road noise can be obtained through calculations using acoustic pressure captured by microphones. However, there are many assumptions within this method, such as the omni-directional source radiation character and the perfectly reflective surface of the vehicle body. The complex wheel cover and the gap between the vehicle body and the ground may also have unfavourable effects on these assumptions. Additionally, vibration-induced noise from the vehicle itself and wind turbulence noise may increase the measurement uncertainty, especially at high speeds.

This study proposes a new methodology for *SWL* measurement of tyre/road noise based on modifications of the PolyU Mark III CPX trailer enclosure, which is currently designed and fabricated for tyre/road noise measurement [10], as shown in Figure 1. All compulsory certification tests stipulated in ISO 11819-2 standard [6] have been completed and satisfied. With the Mark III CPX trailer modified to be a reverberant chamber, the new methodology for *SWL* measurement of tyre/road noise can be carried out. A reference sound source (RSS) with a known *SWL* is applied in the reverberant chamber, and the sound pressure level (*SPL*) distributed inside is measured and arithmetically averaged over different locations. The relationship between *SWL* and *SPL*, which depends on the specification of the reverberant chamber, can be obtained. During road tests, another series of *SPL* generated by tyre/road noise can be captured at specific vehicle speeds, and the *SWL* of tyre/road noise can be deduced using the principle of comparison method like BS EN ISO 3741 standard [11].

(a)

(b)

Figure 1: Overview of the PolyU Mark III CPX trailer enclosure.

2. PHYSICAL PRINCIPLE AND METHODOLOGY

A reverberant chamber was built up with diffuser panels installed on the interior surfaces of the Mark III CPX trailer enclosure. The absorption materials lined on the interior walls/ceiling stayed untouched for insulating the exterior noise from the other passing-by vehicles and absorbing the vibration-induced noise from the trailer enclosure itself. All diffuser panels must be properly designed and tightly fastened to the walls of the enclosure to make sure there is no coupling between structural modes of the panels and the acoustic modes in the enclosed field. The principles for designing the reverberant chamber obey the rule that the acoustic resonance shall be avoided, and the room modes of enclosure volume shall be eliminated. This means that the noise energy distribution within the enclosed field must be controlled as uniform as possible. In view of this objective, none of the same panels were placed face-to-face within the enclosure so as to reduce the probability of generating acoustic resonance between the panels and consequently the room modes can be suppressed. The panels fixed on the ceiling must have curved surfaces for all the designs to minimize the resonance induced by the reflected waves from road surface.

It is known that the dimensions of the boundary diffusers might have a significant influence on the sound field diffusion in the chamber reverberant space [12]. Several layouts of the diffuser panels were designed and analysed with the finite element simulation for comparing their acoustic performance. The final design carrying the most diffused field was finally determined for further fabrication and installation. The reverberant panels and the ground surface were set as perfectly reflective surfaces in the numerical simulation. The size of tyre followed the standard reference test tyre (SRTT). The noise source locations as well as the strength were kept the same for all the numerical models. The *SPL* distributions on the specific horizontal planes were chosen for describing the acoustic behaviours within the enclosed space and contours obtained from different reverberant chamber designs were taken into comparisons and analysis. The values of *SPL* within the reverberant chamber simulations were all captured from locations at least a quarter wavelength of the lowest frequency of interest (i.e. 315 Hz) away from the boundary diffuser surfaces, as suggested in the studies of the reverberant room design [13]. The overview of the optimal design of the reverberant chamber is shown in Figure 2 and some of its *SPL* contours on a vertical plane passing through the tyre are shown in Figure 3.

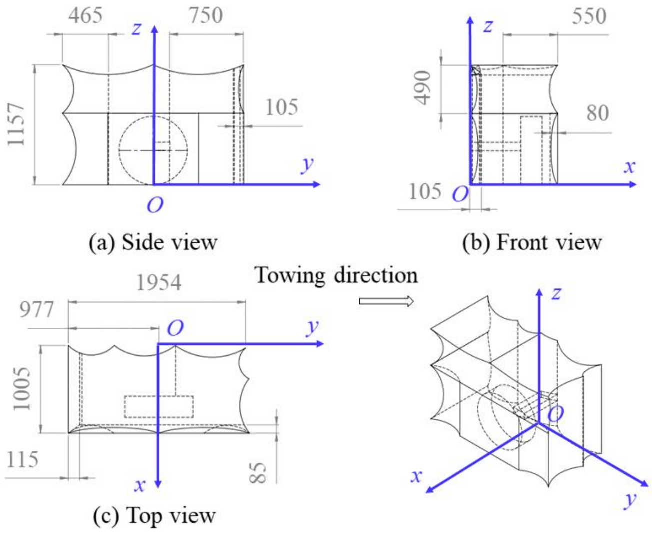


Figure 2: The optimal design of the reverberant chamber within trailer enclosure (in mm).

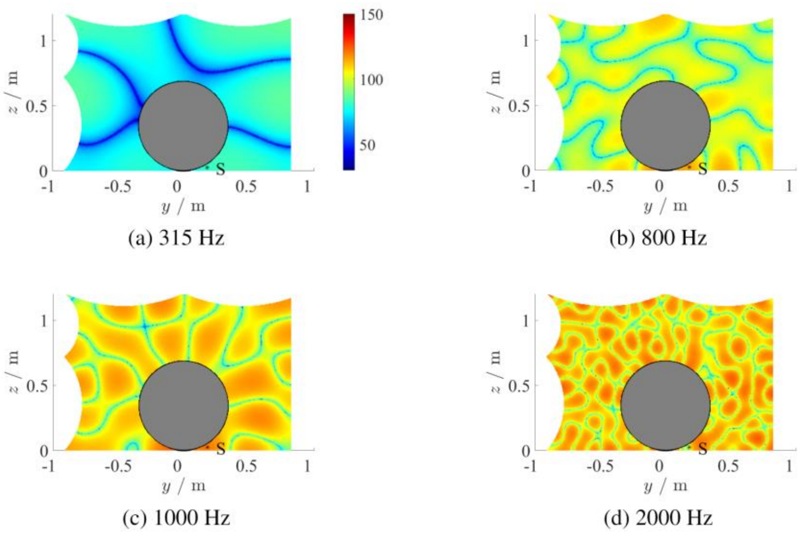


Figure 3: Distribution of *SPL* for the optimal design of reverberant chamber.

The flow of the sound power generated from the source in a limited space constitutes three aspects, namely acoustic energy distributed in the reverberant volume, acoustic energy absorbed and the leakage. The performance of noise insulation of the enclosure had been guaranteed through the compulsory certification tests according to ISO 11819-2 standard [6]. It means that the noise leakage of the reverberant chamber was considered minimal for the tyre/road noise measurement. As all the absorptive materials were covered by the fully reflective diffuser panels, the absorption behaviours of the acoustic energy were minimized.

In the theory of reverberant acoustics in enclosure, the *SPL* measurement in the diffused field with a noise source of known *SWL* can be expressed as [13],

$$SPL = SWL + 10\log_{10}\left(\frac{4}{R}\right), \tag{1}$$

where $R = S_A\,\alpha_{avg}/(1 - \alpha_{avg})$ is the room constant, which is normally used to describe the acoustical characteristics of a room or chamber. The quantity S_A is the total absorbing surface area in the chamber and α_{avg} is the spatially averaged absorption coefficient. Therefore, the relationship between measured *SPL* and the *SWL* in the reverberant chamber can be examined against the theory for assessing the acoustic performance of the reverberant field and then the *SWL* of the tyre/road noise can be predicted with the captured *SPL*.

Taking the principles of comparison method detailed in BS EN ISO 3741 standard [11], a RSS of known *SWL* is properly applied in the reverberant chamber to estimate the *SPL* distribution inside. The *SWL* of the RSS fed with white noise at a specific signal level is named as SWL_r , whereas the averaged *SPL* obtained over the reverberant space under static condition is named as SPL_r . During the road tests with a moving reverberant chamber, the *SPL* captured on the same microphone locations as the static ones are averaged again to obtain a new *SPL* in the diffused volume, which is named as SPL_t . Following the principle of the comparison method, the *SWL* spectra of the tyre/road noise at a specific vehicle speed, denoted as SWL_t , can be calculated by [11]:

$$SWL_t = SPL_t + (SWL_r - SPL_r) + C. \tag{2}$$

The constant *C* is the radiation impedance correction in dB which accounts for the meteorological effects on measured sound power during the measurement. The following equation is valid for a monopole point source and applies as a mean value for other sources [11]:

$$C = -10\log_{10}\left(\frac{p_s}{p_0}\right) + 15\log_{10}\left(\frac{273.15 + \theta}{\theta_0}\right), \tag{3}$$

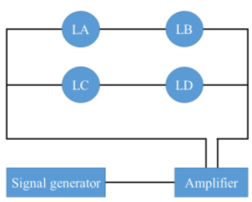
where p_s is the static atmospheric pressure in kPa during the test, p_0 is the reference static pressure equals to 101,325 kPa, θ is the air temperature in degrees Celsius at the time and place of the test, θ_0 is the reference temperature equal to 296 K.

3. SOUND POWER LEVEL MEASUREMENT OF THE TYRE/ROAD NOISE

3.1. Basic Experimental Setup

In the present study four loudspeakers were combined to form the RSS for the *SWL* measurement within the reverberant chamber. Each pair of loudspeakers is connected serially, and the pairs were then put in parallel to amplify the signal supply from the amplifier. White noise was used for all measurements in the reverberant chamber in both static and road tests. Figure 4 shows a view of the loudspeakers and the connection for composing the RSS for the present study.

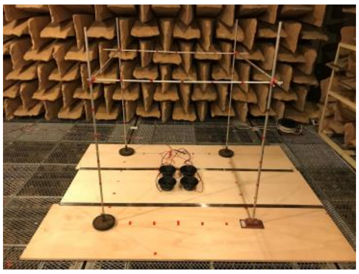
(a)



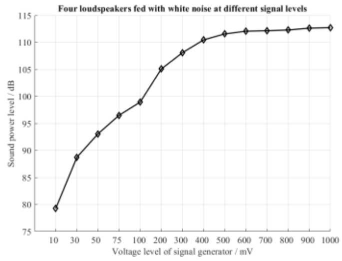
(b)

Figure 4: (a) Signal loudspeaker; (b) loudspeaker combination for RSS. Lx - loudspeaker x, x=A, B, C, D.

The *SWL* of the RSS, fed with white noise at various signal levels, was measured using the scanning method specified in EN ISO 9614-3 standard [14]. The measurement was conducted with an intensity probe in the anechoic chamber at the Department of Mechanical Engineering, The Hong Kong Polytechnic University. The RSS was located on a perfectly reflective surface on the ground, and a cubic frame was built around the RSS to capture acoustic pressures in all directions through the five partial scanning surfaces. Figure 5 shows the experimental setup and the measured results.



(a)

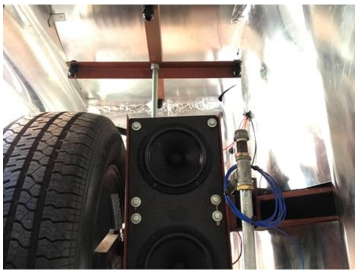


(b)

Figure 5: Measurement of the *SWL* of RSS in the anechoic chamber.

Following the optimal design of the reverberant chamber deduced from finite element simulations (Figure 2), aluminium reverberant panels were fabricated and installed on the interior walls/ceiling of the Mark III CPX trailer enclosure to cover the absorption materials on the interior walls (Figure 6). With the *SWL* of the RSS and the *SPL* obtained from specific microphone locations, the difference between *SWL* and the *SPL* for this reverberant chamber could be calculated. When the spatially averaged *SPL* of the tyre/road noise was measured during the road test at certain vehicle speed, the *SWL* of the tyre/road noise could be deduced from Equation 2 with consideration of atmospheric parameters during the tests.

(a)



(b)

Figure 6: Microphones and RSS setting in the reverberant chamber.

It is always preferred to have the experimental conditions for the measurement of the unknown tyre/road noise source in the reverberant chamber the same as that for the RSS [11]. As the *SPL* measurement of the tyre/road noise has to be performed when the reverberant chamber is running, the effects of chamber motion on the measured results are unknown. They might bring out significant disturbances to the deduced *SWL* of the tyre/road noise if the comparison method. Therefore, the feasibility of using such a comparison method had to be validated first before actual *SWL* measurement of the tyre/road noise. As such a methodology based on static tests and road survey with RSS was introduced and described in following sections.

3.2. Quantification of Chamber Acoustical Characteristics

The acoustical characteristics of the chamber must be known for the execution of the proposed methodology. The relationship between the SPL of the uniform reverberant sound field excited by a source inside is particularly needed. As such, the quantification of chamber acoustic characteristics was carried with carefully set static and road tests with the chamber.

The static measurements in the reverberant chamber were conducted in a workshop in rural area in Yuen Long, New Territories in Hong Kong which gave an ambient environment of very low background noise level. The RSS was driven by specific signals at microphone locations specified in the previous section and the SPL_r captured at microphone locations in the reverberant space were averaged arithmetically. Generally, for the SPL_r in the reverberant chamber increases with increasing voltage levels fed to the RSS (Figure 7(a)). With the SWL_r of RSS determined separately in anechoic chamber, the linear regression of SWL_r could be expressed in terms of SPL_r in the reverberant chamber whose slope was found close to unity (Figure 7(b)). With reference to Equation 1, it can be concluded that the good linearity between SWL_r and SPL_r confirms that the prediction of SWL using the measured SPL within such a small reverberant chamber is feasible.

(a) (b)

Figure 7: (a) Averaged *SPL* inside the reverberant chamber. (b) Linear regression fit between *SWL* and *SPL*.

Road tests were conducted for testing the developed methodology of the measurement of sound power of tyre/road noise at different vehicle speeds. During the road tests, the RSS within the reverberant chamber was switched on and provided with various signal levels. For each road test, the RSS was excited with a signal of level set for that speed and data sampling was continued for 15 seconds. Each measurement was repeated twice in each test. Road tests were carried out on two types of roads, namely Tin Ying Road with WC10 surface and Yuen Long Highway with PMFC10, at selected vehicle speeds. It was important to ascertain the sensitivity of RSS radiation to vehicle speed. The SPL_t obtained inside the reverberant chamber running at different vehicle speeds with the RSS turned on are shown in Figures 8 and 9. At the same RSS signal input, the measured SPL_t at all tested vehicle speeds (Figures 8(a), 8(c), 9(a) and 9(c)) do not show significant deviation from that obtained at zero speed (Figure 7(a)). Therefore, the linear regressions of SWL_t with respect to SPL_t driven by increasing signal levels for each vehicle speed can be deduced at various speeds (Figures 8(b), 8(d), 9(b) and 9(d)).

(a) (b)

Figure 8: The SWL measurement of tyre/road noise on Tin Ying Road (WC10 surface). (a) Averaged *SPL* and (b) its linear regression fit at 40 km/h. (c) Averaged *SPL* and (d) its linear regression fit at 60 km/h.

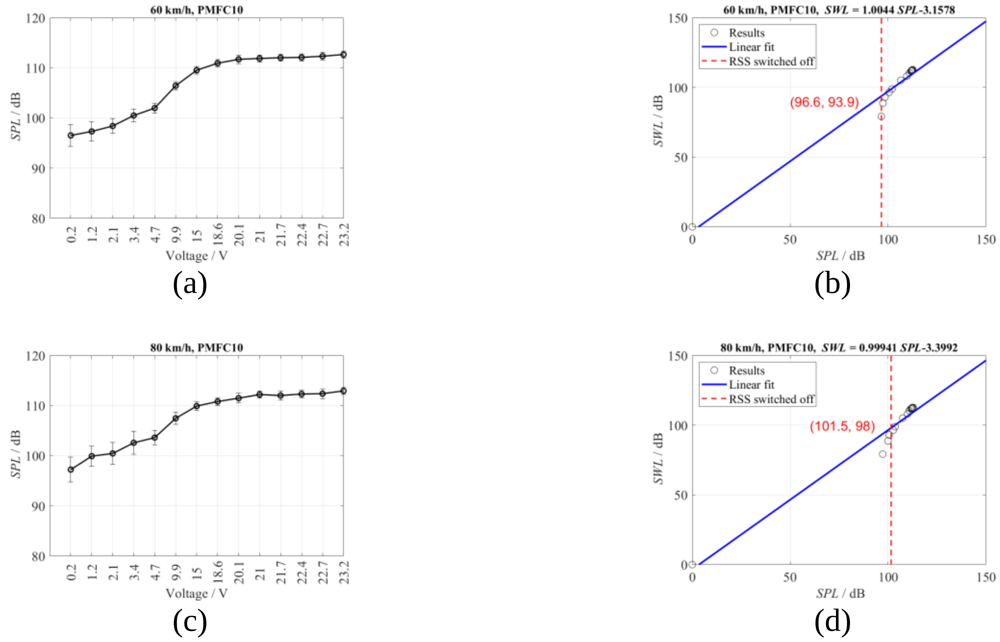


Figure 9: The SWL measurement of tyre/road noise on Yuen Long Highway (PMEC10 surface). (a) Averaged SPL and (b) its linear regression fit at 60 km/h. (c) Averaged SPL and (d) its linear regression fit at 80 km/h.

The linear regression fit describes acoustic response of the reverberant space to given source power radiation. It allows us to estimate the sound power levels of tyre/road noise due to SRTT running on real road surfaces at different speeds. The regression fit may be expressed as

$$SWL_t = a_t SPL_t + b_t, \tag{4}$$

where a_t and b_t are the slope and intercept on *SPL* axis respectively. Their values for the two roads for testing are given in Table 1. The slopes of the linear regression are close to 1 for all road tests irrespective of the vehicle speeds and road surface types. Such consistency provides sound evidence that the linear relationship between SWL_t and SPL_t is robust for the present chamber design. It is interesting to observe that although SPL_t values for WC10 and PMFC10 surfaces at a fixed vehicle speed (e.g. 60 km/hr) do not show significant difference, their respective linear regression results still illustrate the slight increase in SWL_t (~ 1 dB) for PMFC10 over that for WC10. Evidently this shows that the proposed methodology is able to provide good resolution for detecting the variation of tyre/road noise radiation from different road surface types. In addition, the values of a_t and b_t obtained from road tests are very close to a_r and b_r obtained from static test (Figure 7). This observation reveals that the slope and the intercept of the linear regression can be pre-determined and taken for the subsequent *SWL* measurements on roads.

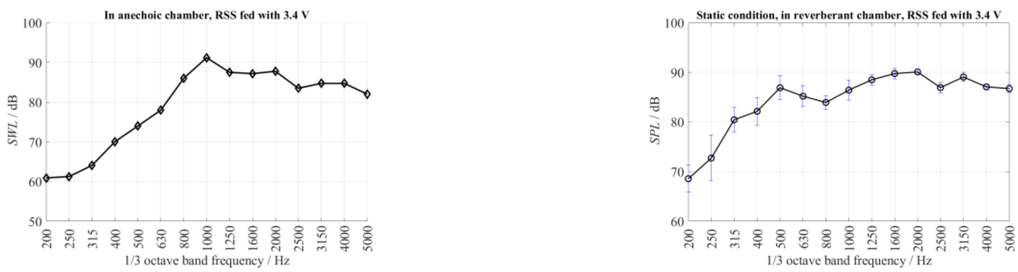
	a_t	b_t
Ting Ying Road (WC10)		
40 km/h	1.0079	-2.5037
60 km/h	1.0067	-2.7711
Average	1.0073	-2.6374
Yuen Long Highway (PMFC10)		
60 km/h	1.0044	-3.1578
80 km/h	0.9994	-3.3992
Average	1.0019	-3.2785

Table 1: Key parameters deduced from linear regression from road tests.

Finally the RSS was switched off to obtain the SPL_t of tyre/road noise produced by the rolling tyre. The SWL_t is readily obtained from a vertical line (red ones in Figures 8 and 9) passing through the SPL_t using Equation 2. Usually, the value of C in the equation is negligibly small in normal weather conditions. For example, at air temperature 23°C and atmospheric pressure, C = 0.01 dB according to Equation 3.

4. ESTIMATION OF SOUND POWER SPECTRUM

The methodology described in Section 3 is primarily developed for the estimation of overall *SWL* of tyre/road noise with the measured *SPL* values obtained from the running Mark III trailer enclosure. The idea can be extended to estimate the *SWL* radiation within a frequency band (e.g. on 1/3-octave banding) so that the *SWL* spectrum can be deduced. To demonstrate the idea, an example of tyre/road noise measurement on Tin Ying Road (WC10) at vehicle speed 70 km/h is briefly described below. In the tests the input to RSS was fixed with a white noise of fixed voltage input 3.4 V. Figure 10 shows the *SWL* measured in anechoic chamber and the spatially averaged *SPL* inside the static Mark III trailer enclosure. The linear regression fit for each frequency band can be deduced from the steps given in Section 3. Consequently, the static a_r and b_r for each frequency band obtained can be taken for the estimation of *SWL* radiation in the same band in road test (Figure 11).



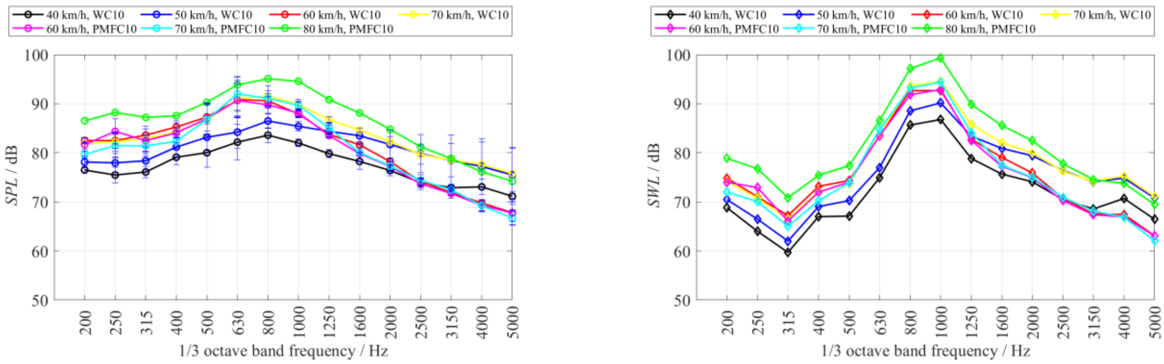
(a) (b)

Figure 10: (a) *SWL* spectrum of RSS measured inside anechoic chamber. (b) Spatially averaged *SPL* spectrum obtained from static Mark III trailer enclosure with same RSS settings.

(a) (b)

Figure 11: (a) Measured spatially averaged SPL_r on Tin Ying Road (WC10) at vehicle speed 70 km/h and (b) the *SWL* spectrum deduced from it.

Using the same methodology as in the example, the *SWL* of tyre/road noise and its spectrum at other vehicle speeds on different road surfaces can be measured and analysed. Figure 12 shows the results obtained from testing on Tin Ying Road (WC10) and Yuen Long Highway (PMFC10).



(a) (b)

Figure 12: The SPL_r and *SWL* spectra obtained from Tin Ying Road (WC10) and Yuen Long Highway (PMFC10) at different vehicle speeds.

It can be observed from Figure 12 that generally the *SWL* increases with vehicle speed and the dominant frequency range of the tyre/road noise power lies within 315 Hz to 2000 Hz. This is consistent with the measurement results of previous ordinary CPX study on same roads. It is interesting to note that the difference in SWL spectra of both types of road surface are not significant at vehicle speeds 60 km/h and 70 km/h. This is seldom observed in previous ordinary CPX studies. More comprehensive investigations into the effects of road surface types on the SWL of tyre/road noise with more road tests are required in future.

5. CONCLUSIONS

This study proposes a new methodology for measuring the sound power level (*SWL*) of tyre/road noise at specific vehicle speeds. The methodology is based on the relationship between the SWL of a specific noise source and the sound pressure level (*SPL*) within a newly designed reverberant chamber for PolyU Mark III trailer enclosure. A comparison method is introduced and applied to obtain the *SWL* spectra of the tyre/road noise with a reference sound source (RSS) generating noise in the reverberant chamber during road tests at various vehicle speeds on specific road surfaces. The optimal design of the reverberant chamber is first determined using numerical methods, with the aim of achieving the least acoustic resonance and the most diffused acoustic energy distribution. Road tests are then conducted to measure the *SPL* within the reverberant chamber, with the RSS driven by various signal levels. By linearly fitting the *SWL* curve with respect to the spatially averaged *SPL*, the *SWL* of the tyre/road noise at specific vehicle speeds can be deduced using the *SPL* generated by the tyre/road noise only with the RSS switched off. Furthermore, with the RSS driven at a fixed signal level, the *SWL* spectra of the tyre/road noise can also be deduced using the comparison method once the *SPL* spectra for the tyre/road noise are measured in the reverberant chamber at any specific vehicle speed.

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