On Application of Sound Power Radiation of Rolling Tyre Measured Using CPX-Based Methodology

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ABSTRACT

The present paper provides a comprehensive account of sound power radiation measurement from a rolling tyre, utilising a methodology that employs an advanced PolyU Mark III Close-Proximity (CPX) trailer enclosure which is aimed to provide CPX measurement per relevant ISO stsandard with suppressed background noise within the interior. The interior walls and ceiling of the enclosure are equipped with diffuser panels, creating a reverberant environment suitable for sound power measurement using the comparison method. The optimal design of the enclosure, which minimizes acoustic resonance and ensures a uniform distribution of acoustic energy, is determined through extensive numerical simulations. During tyre/road sound power measurements, the spatially averaged sound pressure level (SPL) distributions within the enclosure are obtained with a reference sound source (RSS) of known sound power. The relationships between the RSS SWLs and the corresponding SPLs are established at all vehicle speeds. These relationships can then be utilised to deduce the total SWL, as well as its 1/3-octave spectrum, from the captured averaged SPL radiated by a tyre rolling at any vehicle speed. The effectiveness of the CPX-based sound power measurement are illustrated. Additionally, the potential of utilising the measured SWLs for predicting pass-by noise radiation to roadside is discussed.

1. INTRODUCTION

There is growing evidence that transportation noise contributes to a wide range of adverse health, social, and economic effects [1–4]. In general, road traffic noise is emitted by the engine, exhaust, aerodynamics, and the interaction between the tyre and road surface. When the vehicle speed exceeds 50 km/h, the tyre/road noise becomes the predominant source of road traffic noise generation [5]. Nowadays, tyre/road noise poses a growing problem, especially in highly urbanised cities like Hong Kong, where traffic is rapidly increasing. With the increasing 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 EN ISO 11819–2 standard [6]. In this method, test tyres are covered by an semi-anechoic trailer 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

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it would in an open area with no enclosures. Li and Leung [7] developed a numerical approach for the design and optimization of the properties of the absorption materials/structures and the uniformity of noise field inside the enclosesure. They developed a new PolyU Mark III CPX Trailer (a.k.a. Mark III trailer) which gives a much suppressed enclosure internal background noise [8] for more accurate and reliable tyre/road noise measurement than the design for its predecessor PolyU Mark II CPX Trailer (a.k.a. Mark II trailer) [9]. The Mark III satisfies all the compulsory certification tests stipulated in EN ISO 11819–2 standard [6].

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 [10] and Coast-By tests on the roadside [11] to measure *SWL*. However, the noise generated by tyres rolling against drum segments is different from noise generated by rolling over 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. Campillo-Davo et al. [12] proposed an alternative CPX measurement method in which additional microphones were added to an extended frame, in conjunction with the mandatory microphones specified in the EN ISO 11819–2 standard [6]. The frame was specifically designed to be affixed to the vehicle body, ensuring that all microphones were positioned on a quarter-spherical surface that directs towards the tyre/road contact patch, capturing incident noise levels of the rolling test tyre. The *SWL* of tyre/road noise can be obtained through calculations utilising the acoustic pressure captured by the microphones. However, there exist numerous assumptions within this method, such as the omni-directional radiation characteristics of the noise source and the perfectly reflective surface of the vehicle body but their validity was questionable. The presence of a complex wheel cover and the gap between the vehicle body and the ground may also have detrimental effects on these assumptions. Additionally, noise induced by vehicle vibration itself and turbulence caused by wind may amplify the measurement uncertainty, particularly at high speeds.

To overcome the aforementioned challenges, Li et al. [13] proposed and validated a novel approach for measuring the *SWL* of tyre/road noise using the CPX methodology. They took advantage of the low background noise within the interior of the Mark III trailer enclosure [8], as depicted in Figure 1. Essentially, they modified the interior of the Mark III trailer enclosure to create a reverberant test space, enabling *SWL* measurement based on the principles outlined in the BS EN ISO 3741 standard [14]. Moreover, they developed a reference sound source (RSS) with a known *SWL* to facilitate the measurement process. By activating the RSS, they established the relationship between *SWL* and the *SPL* averaged across all microphone locations when the test space is stationary. This relationship was found to be specific to the design of the reverberant test space. The authors then successfully determined the *SWL*s of tyre/road noise for various combinations of road surface types and vehicle speeds. The CPX *SWL* measurement results proved to be more effective in identifying the primary spectral contributions to tyre/road noise compared to the conventional CPX *SPL* measurement specified in the EN ISO 11819-2 standard [6].

The purpose of this paper is to provide an account of the accomplishments in CPX sound power measurement using the Mark III trailer and suggest potential applications for the measured *SWL* of tyre/road noise.

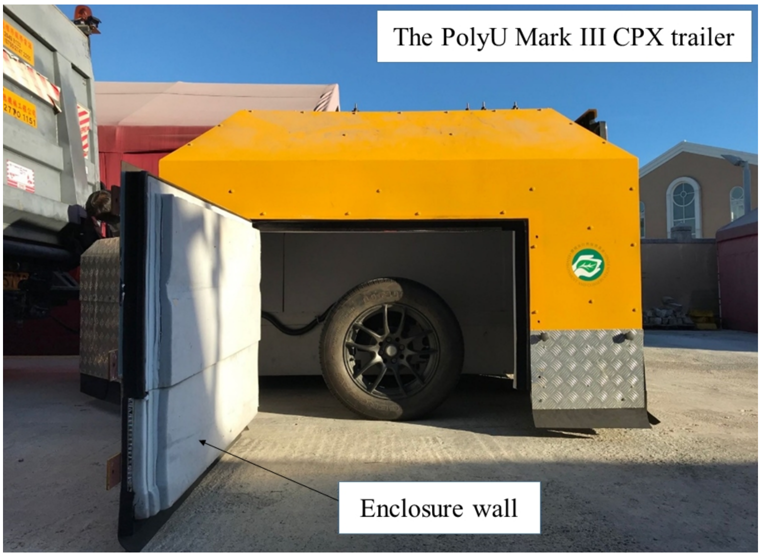


Figure 1: Overview of the enclosure of PolyU Mark III CPX trailer (Mark III trailer).

2. CPX-BASED SOUND POWER MEASUREMENT

2.1. Basic Measurement Principles

According to Li et al. [13], a reverberant test space was constructed, with reflective diffuser panels installed on the interior surfaces of the Mark III trailer enclosure. The absorption materials lining the interior walls and ceiling were left untouched, serving to insulate the exterior noise from passing vehicles and absorb vibration-induced noise from the trailer enclosure itself. The performance of noise insulation of the enclosure had been guaranteed through the compulsory certification tests according to EN ISO 11819-2 standard [8,9]. The noise leakage of the reverberant chamber was considered minimal for the tyre/road noise measurement.

It is crucial that all reflective diffuser panels are meticulously designed and securely attached to the walls of the enclosure, ensuring there is no coupling between the structural modes of the panels and the acoustic modes within the enclosed space. During the design of the reverberant test space, there was a requirement to avoid acoustic resonance and eliminate the room modes of the enclosure volume. This necessitates maintaining a uniform distribution of noise energy within the enclosed space. To meet this requirement, no two identical panels were positioned facing each other within the enclosure, thereby reducing the likelihood of generating acoustic resonance between the panels and suppressing the occurrence of room modes. Additionally, the panels fixed to the ceiling must feature curved surfaces in all designs to minimize resonance resulting from reflected waves originating from the road surface. Extensive numerical simulations of diffuser configurations were conducted, and the optimal design, which achieved the most uniform *SPL* distributions across all frequencies within the test space, was selected for fabrication.

In the theory of reverberant acoustics in enclosure, the *SPL* measurement in the diffused field driven by a RSS of known *SWL* can be expressed as [14],

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

where $R = S_A\,\alpha_{avg}/(1 - \alpha_{avg})$ is the room constant, 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*.

According to the comparison method detailed in BS EN ISO 3741 standard [15], the *SWL* of the RSS fed with white noise at a specific signal level is named as SWL_r , whereas the averaged *SPL* obtained within the reverberant test space under static condition is named as SPL_r. On the other hand, during the road tests when the reverberant test space is moving, the SPL captured on the same microphone locations are averaged again to obtain a new SPL_t in the same diffused volume. Thus, the SWL_t of the tyre/road noise at a specific vehicle speed can be calculated by [15]:

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

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 valid for a monopole point source characteristics for RSS applies [11]:

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

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, and θ_0 equals 296 K. 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. Therefore, the following linear relation between SWL difference and SPL difference holds

$$SWL_t - SWL_r = SPL_t - SPL_r. \tag{4}$$

2.2. Quantification of Trailer Enclosure Reverberant Characteristics

In order to execute the proposed methodology, it is crucial to ascertain the acoustical characteristics of the reverberant test space within the trailer. Specifically, it is important to comprehend the correlation between the averaged SPL of the uniform reverberant sound field produced by the RSS and its fluctuations in response to varying source input levels (Figure 2). Consequently, the quantification of these acoustical characteristics was undertaken through meticulous static and road tests. For further information, reference is made to the work of Li et al. [13].

(a) (b)

Figure 2: Microphones and RSS setting in the reverberant chamber.

The static quantification measurements in the reverberant chamber were performed in a workshop situated in a rural area in Yuen Long, New Territories, Hong Kong. This location provided a low ambient noise level environment. Quantification road tests were conducted using various combinations of road surface types and vehicle speeds. During these road tests, the RSS within the reverberant chamber was activated and supplied with different signal levels. For each road test, the RSS was stimulated with a signal level specific to that speed, and data sampling continued for 15 seconds. The test tyre used is SRTT. Each measurement was repeated twice in each test. The road tests were carried out on two types of roads: Tin Ying Road with WC10 surface and Yuen Long Highway with PMFC10 surface, at selected vehicle speeds [13]. It was crucial to determine the sensitivity of RSS radiation to vehicle speed. The averaged SPL_t inside the trailer enclosure was recorded while running at different vehicle speeds with the RSS activated. When comparing the averaged SPL_t at all tested vehicle speeds with the RSS signal inputs, no significant deviation was observed from the result obtained at zero speed. Therefore, linear regressions of SWL_t with respect to SPL_t, driven by increasing signal levels, can be deduced for each vehicle speed.

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

$$SWL_t - SWL_r = a_t SPL_t + b_t\,, \tag{5}$$

where a_t and b_t are the slope and intercept on SPL axis respectively. Based on the findings of Li et al. [13], it was observed that the values of slope a_t for all road tests, regardless of vehicle speeds and road surface types, were very close to 1. The value of b_t, on the other hand, seemed to depend on the type of road surface. For Ting Ying Road (WC10) it yielded -2.6374 whereas for Yuen Long Highway (PMFC10) it was -3.2785. This consistent pattern provides strong evidence that the linear correlation between SWL_t and SPL_t remains robust for the current design of the reverberant trailer.

2.3. Measured Sound Power

The methodology described 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 each 1/3-octave frequency band so that the *SWL* spectrum can be deduced. For further information, reference is made to the work of Li et al. [13]. Figure 3 shows the sample averaged *SPL* spectra obtained from testing on Tin Ying Road (WC10) and Yuen Long Highway (PMFC10) and the corresponding *SWL* spectra deduced.

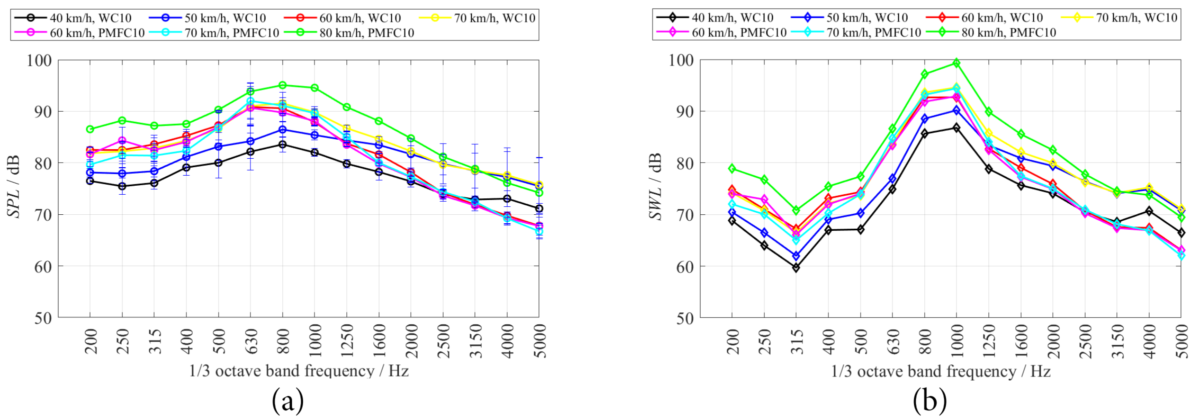


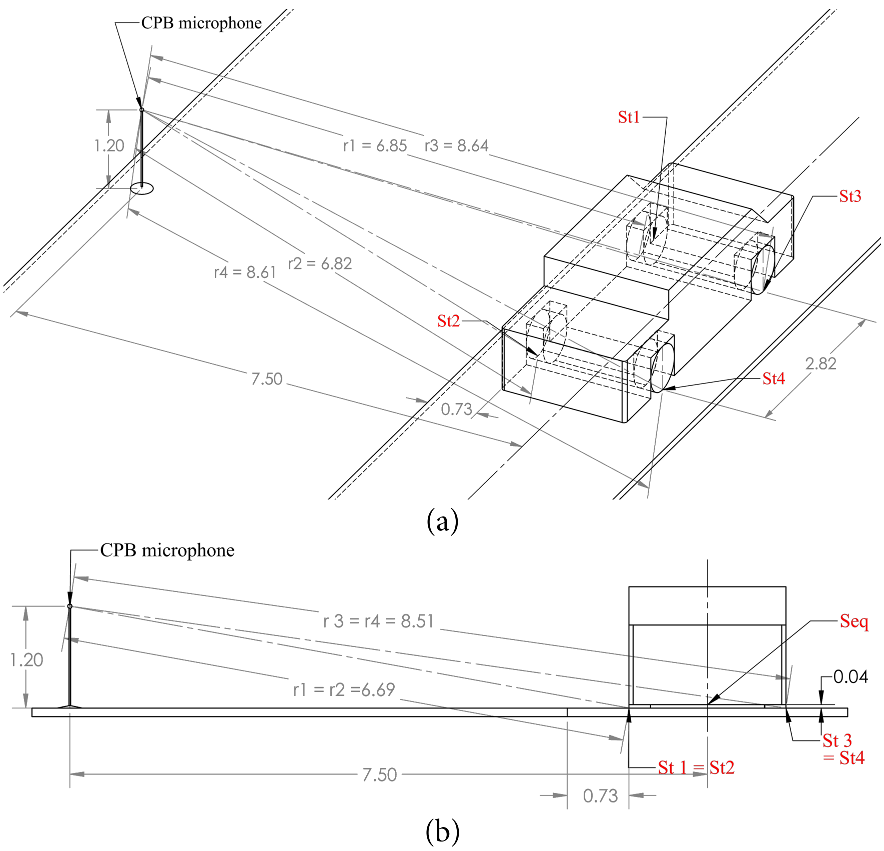
Figure 3: Sample *SWL* spectra obtained from Tin Ying Road (WC10) and Yuen Long Highway (PMFC10) [13].

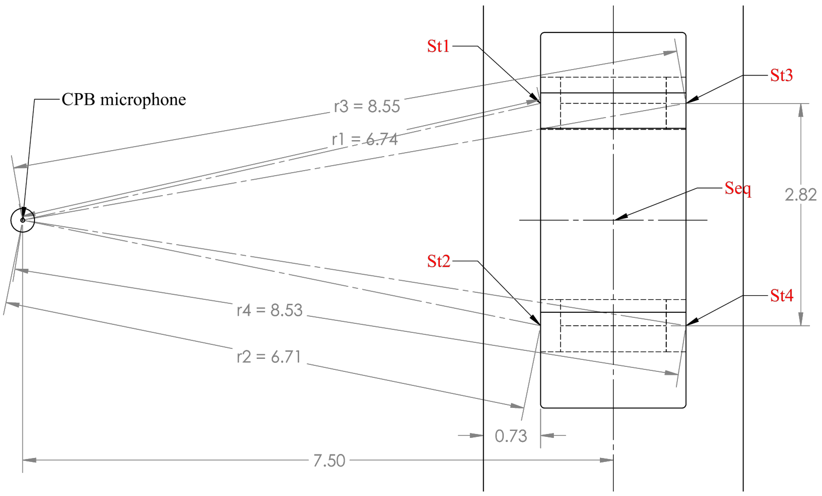
It is evident that, in general, the *SWL* increases with vehicle speed, and the primary frequency range of the power produced by tyre/road noise falls between 315 Hz and 2000 Hz. This observation aligns with the measurement outcomes from previous conventional CPX studies conducted on the same roads. It is worth noting that the disparity in *SWL* spectra between the two road surface types is not significant at vehicle speeds of 60 km/h and 70 km/h, which is a rare occurrence in previous conventional CPX studies per EN ISO 11819–2:2017 standard [6]. Further extensive investigations are necessary in the future to thoroughly examine the impact of road surface types on the *SWL* of tyre/road noise, requiring additional road tests.

3. APPLICATION OF MEASURED SOUND POWER LEVEL

Methods for measuring tyre/road noise can be broadly classified into two categories: pass-by methods, where a microphone is positioned at the roadside to measure the noise emitted by passing vehicles (e.g. controlled pass-by with setting of EN ISO 11819–1:2023 [16]), and onboard methods which utilise acoustic sensors to measure noise in proximity to the rolling tyre (such as EN ISO 11819–2:2017 [6]). Several studies [17,18] employed extensive sets of CPB and CPX noise measurements for different tyre types on various road surfaces, with the aim of highlighting the strong statistical correlation between road surface texture and tyre/road noise. Pass-by measurements were widely used to calibrate hybrid statistical models [19] and investigate the mechanisms of tyre/road noise generation through speed exponent analysis [20]. It is worth noting that CPX measurements were used for the hybrid statistical estimation of noise levels by correlating them with calculated contact force spectra [21].

Generally, the measured CPB and CPX sound pressure levels (i.e. SPL_{CPB} and SPL_{CPX}) are different even though sometimes they show similar spectral distributions. This difference is not constant and is mainly due to different geometrical configurations and different propagation paths. The relationship between SPL_{CPB} and SPL_{CPX} is a subject of ongoing interest within the tyre/road noise community [22]. It is envisaged to serve not only to validate various measurement methods but also to develop prediction models that describes how the SPL_{CPX}, which represent the radiation of the noise source, propagates away and determines the SPL_{CPB}, which indicate the nuisance perception of the noise-sensitive receivers, on the roadside. Anfosso-Ledee [23] presented an interesting attempt in modeling of such local propagation effects by means of a propagation filter which establishes the relationship between SPL_{CPB} and SPL_{CPX}. Figure 4 shows an overview of pass-by setting following the requirements in EN ISO 11819–1:2023 [16]. It shows the moment when the passing vehicle is the closet to the microphone. The dimensions of the vehicle adhere to those specified for an Audi A6 [24].





(c)

Figure 4: (a) Schematic illustration of the problem setting, CPB microphone, and the locations of sources. (b) Rear view. (c) Top view. The tyre/road noise sources S_{tyre} are indicated by S_{t1}, S_{t2}, S_{t3} and S_{t4}.

According to Anfosso-Lédée [23], the propagation filter ΔL, may be defined as

$$\Delta L = SPL_{CPX} - SPL_{CPB} \tag{6}$$

Here the SPL_{CPX} and SPL_{CPB} are the values of SPL measured at CPB microphone (Figure 4) due to the tyre/road noise source S_{tyre} at a tyre contact patch (with sound power level SWL_{tyre}), and to an equivalent source S_{eq} (with sound power level SWL_{eq}) of the vehicle which takes only the tyre/road noise into account. Assuming a point source characteristics, the following holds

$$SPL_{CPB} = SWL_{eq} - 10\log_{10}(4\pi r_{eq}^{2}) + 10\log_{10}(D) + Att_{CPB} \tag{7}$$

where r_{eq} is the distance between the CPB microphone and the equivalent vehicle source S_{eq} location, and Att_{CPB} is the sound attenuation relative to free field propagation that occurs in between, $D = 2$ is the directivity factor [14]. In a similar fashion,

$$SPL_{CPX} = SWL_{tyre} - 10\log_{10}(4\pi r_{CPX}^{2}) + 10\log_{10}(D) + Att_{CPX} \tag{8}$$

where r_{CPX} is the distance between the CPB microphone and a source S_{tyre} location, and Att_{CPX} is the corresponding sound attenuation. Note that the point source assumption for the sources is valid only at higher frequencies > 200 Hz [23]. The Equations 6 to 8 may be combined to give

$$\Delta L = (SWL_{tyre} - SWL_{eq}) + (Att_{CPX} - Att_{CPB}) + 20\log_{10}(r_{CPB} / r_{CPX})\,. \tag{9}$$

Once ΔL is known, the SPL_{CPB} is readily calculated using Equation 6 with the input of SPL_{CPX} obtained from conventional CPX measurement with the same kind of tyres on the same road surface. Considering the symmetry of the problem (Figure 4(c)), incoherent source radiation and assuming same values of S_{tyre} on the same side of the vehicle, the propagation filter ΔL may be further simplified to a form that depends on the difference in sound attenuation and all distances shown in the figure [23]. In situations where the entire surface between the vehicle and CPB position is purely reflective, ΔL becomes a constant value but such situations are not popular in practical situations.

The proposal introduced by Anfosso-Lédée [23] offers an interesting and potential method for estimating SPL_{CPX} using CPX results. Nevertheless, the main obstacle with this approach lies in the challenge of deducing the SWL difference mentioned in Equation 9 in most scenarios. However, this challenge can be overcome by utilising the measurement results obtained through the current CPX SWL measurement methodology, rather than from the conventional CPX measurement approach. A more straightforward approach can be adopted, assuming point source characteristics once again. The contributions of the source at a tyre j can be expressed as follows:

$$SPL_{CPB,j} = SWL_{tyre,j} - 10\log_{10}(4\pi r_j^2) + 10\log_{10}(D) + Att_{CPB,j}, \tag{10}$$

Subsequently, the $SPL_{CPB,j}$ values for each tyre j are accumulated to determine the overall SPL at the CPB microphone. Equation 7 can be employed for each 1/3-octave frequency band to obtain the SPL spectrum. Figure 5 illustrates the deduced $SPL_{CPB,j}$ spectra using the SWL spectra depicted in Figure 3(b) as input, along with the Att_{CPB} information for practical road geometry deduced numerically in Anfosso-Lédée [23].

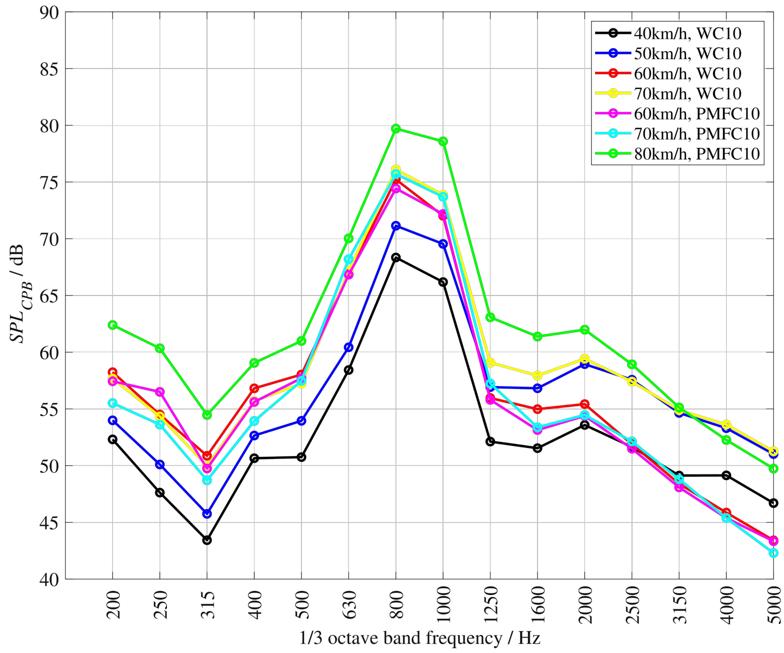


Figure 5: SPL_{CPB} spectra deduced from the measured SWL spectra (Figure 3(b)) for Tin Ying Road (WC10) and Yuen Long Highway (PMFC10).

This direct and inclusive approach, incorporating the sound power level from each tyre as determined by the current CPX SWL measurement method, allows for a more accurate evaluation of noise propagation and ultimately enhances the prediction of SPL distributions in different pass-by noise scenarios. In order to further validate the predictive capability of our technique, CPB measurements will be carried out at various vehicle speeds and on different road surfaces. By comparing the actual sound pressure level measurements with the predicted values, the level of agreement are assessed and their discrepancies can be identified.

4. CONCLUSIONS

The present paper provides a comprehensive examination of sound power radiation measurement from a rolling tyre, utilizing a methodology that employs an advanced PolyU Mark III Close-Proximity (CPX) trailer enclosure. The primary objective of the enclosure is to facilitate CPX measurement in accordance with the relevant ISO standards while effectively minimizing background noise within the interior. The interior walls and ceiling of the enclosure are equipped with diffuser panels, creating a reverberant environment that is well-suited for sound power measurement using the comparison method. The optimal design of the enclosure, which prioritizes the reduction of acoustic resonance and ensures a uniform distribution of acoustic energy, is determined through extensive numerical simulations. During sound power measurements of the tyre/road noise, the spatially averaged sound pressure level (SPL) distributions within the enclosure are obtained using a reference sound source (RSS) of known sound power. The relationships between the sound power level (SWL) of the RSS and the corresponding SPLs are established for all vehicle speeds. These relationships are then utilized to deduce the total *SWL*, along with its 1/3-octave spectrum, based on the captured averaged *SPL* produced by a rolling tyre at any given vehicle speed. With the availability of measured *SWL*, an attempt for its use for the prediction of pass-by tyre/road noise radiation, and it spectrum, to a receiver at roadside in a setting similar to the one stipulated in ISO standard is outlined. Encouraging prediction results are obtained. In order to further validate the predictive capability of our technique, dedicated controlled pass-by (CPB) measurements on realistic roads will be carried out at varying vehicle speeds and on different road surface types. By comparing the actual CPB *SPL* measurements with the predicted values, the level of agreement can be assessed and their discrepancies can be ascertained.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the Environment and Conservation Fund of the Government of Hong Kong Special Administrative Region under grant number ECF 115/2020.

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