Applied Acoustics 143 (2019) 7–18

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

An alternative close-proximity test to evaluate sound power level emitted by a rolling tyre

Nuria Campillo-Davo *, Ramon Peral-Orts, Hector Campello-Vicente, Emilio Velasco-Sanchez

Miguel Hernandez University of Elche, Avda. de la Universidad, s/n, 03202 Elche (Alicante), Spain

ARTICLE INFO

Article history:
Received 14 March 2018
Received in revised form 10 August 2018
Accepted 14 August 2018
Available online 31 August 2018

Keywords:
Tyre
Road
Traffic noise
Sound power level
CPX

ABSTRACT

The noise emission of a rolling tyre is produced by different physical mechanisms generated during the tyre-road interaction, being the main noise source of a vehicle when driving at high speeds. Diverse measurement methods can be found in the literature to assess the rolling noise emission. In that sense, the close-proximity (CPX) method allows to evaluate tyre/road sound level with at least two microphones operating in the close field of the test tyre. This paper presents a new methodology, based on the CPX method, which allows assessing the sound power level of the rolling tyre by introducing some changes in the traditional close-proximity test. The methodology (named A-CPX) has been analytically and experimentally validated, and is finally used to obtain the total tyre/road sound power level emitted by the whole set of tyres of a vehicle.

1. Introduction

Tyre/road noise is one of the main noise sources in a traffic flow. In fact, the rolling noise becomes the most important contribution to the total sound emission, higher than the engine noise in an internal combustion vehicle, when it is circulating at high speed. Previous studies demonstrated that such fact is independent even of the vehicle type. The results presented in [1] show a significant difference in the noise emitted by internal combustion engines and electric engines, especially at speeds below 50 km/h. But, above that speed, it is possible to assume the noise emitted by an electric vehicle as the noise emitted by an internal combustion engine vehicle without mechanical noise.

Different methods are collected in the literature to assess tyre/road noise, some of them are standardized methods and others are specifically designed for research purposes. Among the first group, the Coast-By (CB) method [2] is the current method for the approval of tyres, based on measurements at 7.5 m of the test vehicle when it passes with the engine switched-off and the transmission in neutral. The Close-Proximity (CPX) method [3] is much extended in the research field, and it is based on sound pressure measurements in the near field of the tyre/road interaction.

The CPX method proposes two different alternatives for measurement: the test tyre is installed in a trailer, and the trailer is towed by a vehicle; or the test tyre is directly mounted on the vehicle. The debate about benefits and drawbacks of each configuration is open. Some authors prefer to use an open trailer [4,5], whilst others choose to use a covered trailer [6–8], and some research groups install the measurement microphones on the test vehicle [9–11]. The trailer solution avoids any wind noise disturbances but sound reflections are generated inside the chamber, in contrast with the vehicle solution that may be affected by wind noise but there are no added sound reflections.

A common feature of most of the tyre/road noise studies collected in literature is the resulting magnitude. Most of them provide their results as an expression of the sound pressure level, but just a very few assess the sound power level [12–14], and mostly are used in traffic noise prediction models [15,16]. The benefit of providing the power level of a sound source is the invariability of such parameter, as it is independent of factors as environment, attenuation or distance.

The work presented in this paper defines an alternative methodology, named alternative close-proximity (A-CPX), to assess the tyre/road noise sound power level of a rolling tyre installed on a car while it is being driven on a road. The analytical and technical viability of the methodology are validated by means of a theoretical study and a series of field measurements, respectively. The results obtained with the A-CPX test are used to obtain the tyre/road sound power level of the whole vehicle, which is finally compared with other experimental results found in the literature.

* Corresponding author.
E-mail address: ncampillo@umh.es (N. Campillo-Davo).

https://doi.org/10.1016/j.apacoust.2018.08.017
0003-682X/

2. The alternative close-proximity (A-CPX) methodology

The novel A-CPX methodology has been designed for evaluating the sound power level emitted by a rolling tyre, by means of sound pressure level measurements. The methodology is based on the procedures described in the ISO 11819-2 standard [3] and also on the ISO 3744 [17]. The major difference regarding the traditional CPX method lies on the microphone locations, since in the A-CPX method these are located in further distances than in the traditional one. Such fact allows to assume that measurements are made in acoustical far field, as it will be illustrated in the next sections. The test tyre is directly boarded on the test vehicle, instead of using a trailer, in order to avoid sound reflections and to ease instrumentation setup.

The initial hypothesis is to consider the tyre as a static, omnidirectional, point source located on two reflecting planes: the road surface and the vehicle body. The power level emitted by the source is assumed to be proportional to the mean root square of the sound pressure, averaged in time and space.

An imaginary parallelepipedic surface must be defined surrounding the test tyre, which should not be installed on a drive nor steering axle, see Fig. 1. The characteristic dimension of the source, $d_{0\_A\text{-}CPX}$, is determined by the Eq. (1).

$$d_{0\_A-CPX} = \sqrt{(l_1/2)^2 + l_2^2 + l_3^2} \quad (1)$$

As the noise source is considered to be located on two reflecting planes, microphone positions will be distributed over an imaginary surface, quarter-sphere shaped. The radius of this surface should satisfy the condition expressed by the Eq. (2), in which the characteristic dimension of the source, $d_{0\_A\text{-}CPX}$, should be previously rounded to the higher integer. Likewise, it is recommended that the radius of the surface never be less than 1 m and preferably should have an integer value.

$$r_{A-CPX} > 2 \cdot d_{0\_A-CPX} \quad (2)$$

Microphone positions are distributed over the surface according to the coordinates collected in Table 1. The Fig. 2 shows a comparison of the microphone positions for the traditional CPX test, Fig. 2a, and the microphone positions for a radius of 1 m in the A-CPX, Fig. 2b. After studying different alternatives, presented in the Section 4, it is recommended to use slender structures for supporting the microphones, in order to avoid air turbulences in the surroundings of the microphones that might influence the measurements.

Fig. 1. Parallelepipedic reference surface defined for the A-CPX test.

Table 1
Microphone position coordinates.

Microphone position	x/r	y/r	z/r
A-CPX Front down	0.86	0.50	0.15
A-CPX Rear down	−0.86	0.50	0.15
A-CPX Middle	0	0.89	0.45
A-CPX Front top	0.57	0.33	0.75
A-CPX Rear top	−0.57	0.33	0.75

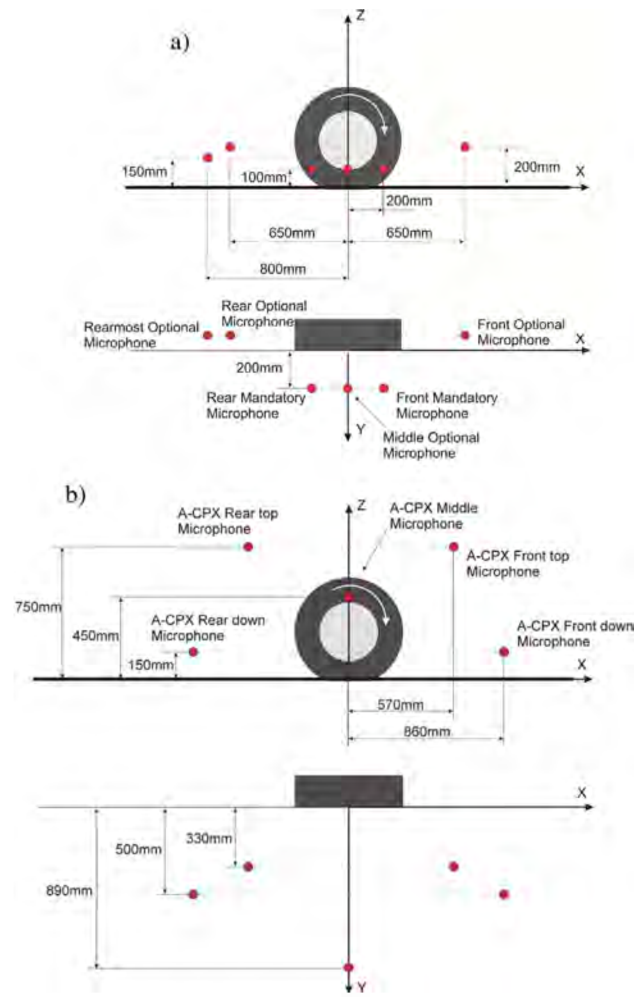

Fig. 2. Comparison of microphone positions: a) the traditional CPX test; b) the A-CPX test for a quarter-sphere surface of 1 m radius.

In an A-CPX test, the vehicle equipped with the test tyre circulates at a reference speed, over a distance of 200 m on the road surface. During the test, the microphones record the sound pressure levels generated by the tyre/road interaction. That procedure is repeated at least 3 times. The microphones are connected to a multichannel data acquisition system that will be located inside the vehicle. The sampling frequency follows the theorem of Nyquist-Shannon, defining the sampling frequency at least twice the maximum frequency of interest. Data is processed in third octave bands.

Vehicle speed is controlled during the test, using a global positioning system (GPS) boarded on the vehicle. Also weather conditions are registered, avoiding wind speeds over 5 m/s.

For the data processing, each road section of 200 m is divided into segments of 20 m. For each segment, it is calculated the equivalent sound pressure level registered by each microphone, according to the Eq. (3):

$$\overline{L_{pi,s\_A-CPX}} = 10 \cdot \log\left[\frac{1}{N} \cdot \sum_{j=1}^{N} 10^{0.1 \cdot L_{pj\_A-CPX}}\right] \text{dB} \quad (3)$$

where $\overline{L_{pi,s\_A-CPX}}$ is the average sound pressure level for the microphone i calculated for the segment s, and for each third octave band, in dB. N is the number of samples of the segment, and $\overline{L_{pj\_A-CPX}}$ is the sound pressure level for the sample j within the segment s, exponentially averaged, for each third octave band, in dB. Fast time constant is recommended for the exponential averaging, and in such case the sampling rate should be one sample per 0.125 s.

Then, the averaged sound pressure level for all the segments included within each road section of 200 m is calculated for each microphone, Eq. (4):

$$\overline{L_{pi,Section\_A-CPX}} = \frac{1}{10} \cdot \sum_{s=1}^{10} \overline{L_{pi,s\_A-CPX}} \text{dB} \quad (4)$$

where $\overline{L_{pi,Section\_A-CPX}}$ is the averaged sound pressure level, registered by the microphone i in the whole section *Section*, for each third octave band, in dB.

The same procedure is applied to average the whole number of repetitions n done at the reference speed (at least 3, as previously commented), and is evaluated according to Eq. (5):

$$\overline{L_{pi\_A-CPX}} = \frac{1}{n} \cdot \sum_{Section=1}^{n} \overline{L_{pi,Section\_A-CPX}} \text{dB} \quad (5)$$

Following, the averaged sound pressure level over the quarter-sphere surface is calculated, using the Eq. (6):

$$\overline{L_{p\_A-CPX}} = 10 \cdot \log\left[\frac{1}{5} \cdot \sum_{i=1}^{5} 10^{0.1 \cdot \overline{L_{pi\_A-CPX}}}\right] \text{dB} \quad (6)$$

Finally, it is calculated the tyre rolling sound power level, according to Eq. (7).

$$L_{w\_A-CPX} = \overline{L_{P\_A-CPX}} + 10 \cdot \log(S_{A-CPX}/S_0) \text{dB} \quad (7)$$

where $S_{A\text{-}CPX}$ is the area of the measurement surface, according to $S_{A-CPX} = \pi \cdot r_{A-CPX}^2$, in square meters, and $S_0 = 1\,\text{m}^2$.

As commented before, the A-CPX is based on the traditional CPX method. Nevertheless, this novel method has also other differences with respect to the CPX, apart from the different microphone locations. The CPX is intended for evaluate the influence on the traffic noise emission of different road surfaces under same traffic conditions. Therefore, it can be used to compare the behavior of different road materials. However, the A-CPX methodology is designed to evaluate noise from the tyre perspective, or even it could be said, from the tyre/road combination perspective, since it is focused on evaluating the tyre-road combination as a noise source. Furthermore, in the A-CPX test, the tyre and the road pavement used during the measurements should not necessarily be standardized or reference elements.

By contrast, some features are shared by both methodologies. In that sense, they have in common that both assume the tyre/road noise as the main vehicle's noise source during the measurement. It is also estimated, in both methods, that there may be background noise influence coming from wind turbulences and both recommend carrying out the measurements when wind speed is less than 5 m/s. The Table 2 shows a comparative scheme that summarizes the main technical differences between both methods.

3. Analytical study

With the aim to study the analytical viability of the proposed methodology, a preliminary simulation was conducted based on the formulation of sound propagation of ideal noise sources.

3.1. Previous remarks

In the current European automotive market, very common tyre dimensions for passenger cars are 195/65R15, 205/55R16, 225/45R17 and 225/40R18. According to Eq. (1), the characteristic dimension, $d_{0\_A\text{-}CPX}$, that correspond to those tyre dimensions, is located in the interval between 735 and 747 mm. And following Eq. (2), a radius of 2 m would be preferable for defining the measuring surface for those usual tyre dimensions. However, the features of the A-CPX methodology involve that microphone locations should be close to the tyre for a proper boarding on the vehicle, and a 1 m radius would be more convenient for the technical viability of the test than using a 2 m radius. Depending on the frequency of interest, the microphone positions in a 1 m radius surface could be located in the close field of the sound source. The threshold between the far and the close fields is limited by the distance to the sound source equal to the wavelength of the lowest frequency of interest. Then, the 315 Hz frequency is the lowest frequency that could be measured using a 1 m radius surface.

The most relevant sound generation mechanisms [18] are produced in the vicinity of the interaction between a tyre and the pavement. Some of those mechanisms radiate noise in the contact region exclusively, whilst some others have a wider radiation area. In the literature are found different works [19,20] related to the identification of noise sources in a rolling tyre. Some authors [21,22] consider as a hypothesis that the whole sound emission is concentrated in a point located on the tyre sidewall, close to the interaction between tyre and pavement. Some others [23,24] propose to characterize a rolling tyre as a set of monopoles located on its surface.

Table 2
Comparative scheme CPX vs A-CPX.

	Measurement Method	
	CPX	A-CPX
Measurement principle	The average A-weighted sound pressure levels emitted by specified tyres are measured over an arbitrary or a specified road distance, together with the vehicle testing speed, by at least two microphones, located close to the tyres	The sound power level emitted by a test tyre installed on a vehicle test and circulating on a road surface, at one or various reference speeds, is evaluated by means of sound pressure level measurements
Measurement results	Tyre/road sound pressure level – CPX level (L_{CPX}) – for the reference tyre and speed and (if using reference tyres) Close-Proximity Sound Index ($L_{CPX:I}$)	A-CPX Sound Power Level for the evaluated tyre/road combination ($L_{W\_A\text{-}CPX}$)
Acoustic field	Near field	Far field
Measurement positions	2 mandatory positions 4 optional positions	5 mandatory positions
Reference speed	50, 80 and 110 km/h	Any speed of interest for the study, from 40 km/h and upwards (where tyre/road noise dominates vehicle noise emission)

Different studies in the literature analyze the contribution of each area of radiation of a rolling tyre, mainly those based on sound intensity measurements [25] and acoustical holography [26]. It is found as a common behavior that the contribution of each area of radiation has a dependency on the frequency, being considered that the emission from the leading edge is slightly higher than the emission from the trailing edge, especially at low and medium frequencies. At the same time, the sound radiation is typically higher at lower areas of the tyre than at the upper areas. However, the upper areas have also an important contribution at low frequencies.

Given these previous remarks, three different cases have been considered for the analytical study, Fig. 3, in order to analyze the effect of the noise sources location, on the sound power level. As the sound emission of a rolling tyre has a complex behavior, it is proposed a simplification based on several point noise sources emitting on the tyre radiation areas. As a first case, the emission has been concentrated on the tyre sidewall, in the center of the contact patch. For the second case, a three noise sources configuration has been proposed: one on the sidewall, one on the trailing edge and one on the leading edge. Finally, a five sources configuration will be considered: the three positions proposed for the second case plus two sound sources on the upper area of the tyre. The position of the sources has been located considering a 175/70 R13 tyre, as such tyre will be used for the experimental tests.

The sources are hemispheric point noise sources, emitting pink noise, located on the tyre surface. The noise source located on the tyre sidewall, in the center of the contact patch, has been considered as a quarter of sphere source, since it is located on the ground plane as well. The ground plane has been modeled as a reflective surface. The receiver locations have been distributed over a 1 m radius quarter-sphere, according to coordinates in Table 1.

The global sound power level emitted by the whole set of sources is the same in all cases under study. However, the individual emission of each source is different and depends on the number of sources per case. Given that this is a preliminary model based on ideal noise sources, the hypothesis of acoustical symmetry has been considered for the vertical plane, mainly based on the usual assumption of low sound directivity of a rolling tyre in the far field [27]. Then, the sources located at the leading and trailing edges in case 2 have the same emission, and have a higher emission than in case 3. In case 3, the sound power emission of the tyre is distributed among the five sources, considering also vertical symmetry and a higher emission at the leading and trailing edges than at the upper areas of the tyre. The Fig. 4 shows the sound power level emitted by the sources, and the total sound power level emission, for the different cases. The relative sound power level of each point

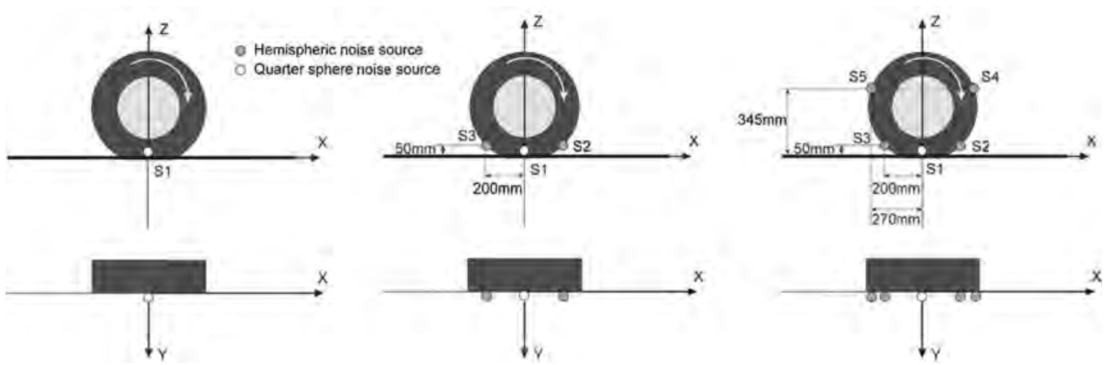

Fig. 3. Location of noise sources for the cases into study.

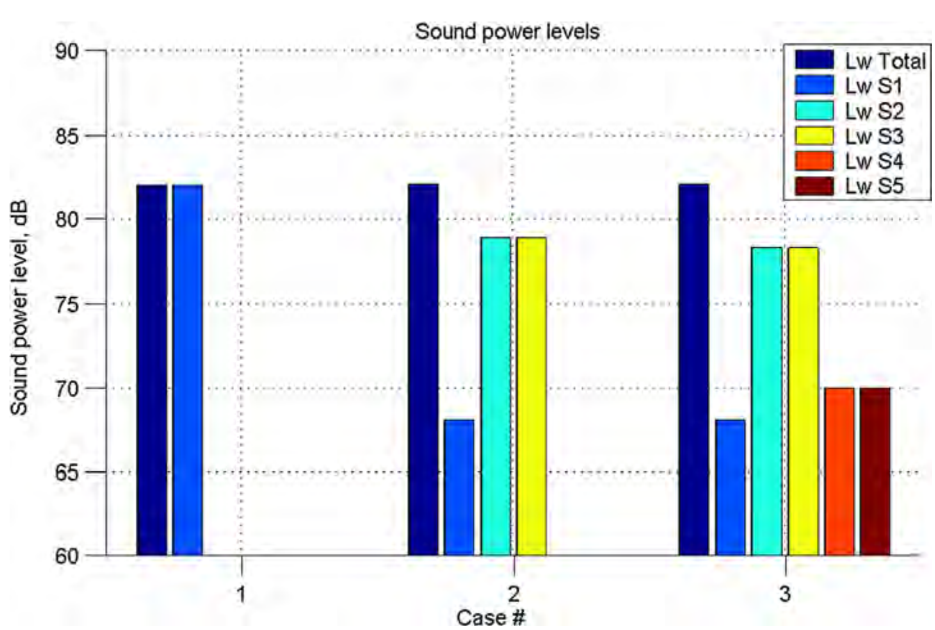

Fig. 4. Sound emission considered for calculations.

source has been estimated according to the experimental results find in the literature [18] for each area of radiation.

3.2. Simulation results

The calculation algorithm developed for the simulation is based on the properties of sound propagation outdoors. If the sound power level of the different noise sources is known, the sound pressure level at the different reception points around the tyre can be calculated. Then, the Eqs. (6) and (7) can be used to evaluate the sound power level of the whole tyre. The simulation results will allow to identify the deviation between the sound power level evaluated by the algorithm and the total emission of the known noise sources. Therefore, it can be identified the differences of considering the tyre as a point noise source or as a distribution of noise sources.

The results of all cases are presented in Fig. 5. The figure shows the global sound power level emitted in each case under study, the sound pressure levels calculated by the algorithm at the receiver positions (including also the traditional CPX locations) and the sound power level calculated by the algorithm.

The sound power level calculated by the algorithm in case 1, equals to the emitted sound power level. That case corresponds to an ideal situation in which the whole emission is concentrated in a single point. The sound pressure levels at the traditional CPX positions are higher than the power level, which reflects the location of the receiver points in the acoustical close field.

In case 2, the emission is located at different points and certain receiver positions are closer to some sources. In that case, the calculated sound power level differs by 0.35 dB from the global emission and small dispersion is observed at the receiver positions. A similar situation results for case 3, where a deviation of 0.48 dB between the emitted and calculated power level is obtained.

3.3. Conclusions of the simulation phase

As it is collected in the literature, the emission of a rolling tyre presents a higher energy concentration at the contact area with pavement, which leads to consider the tyre as a point sound source. However, for short measuring distances it is necessary to take the tyre as a distribution of sound sources. When considering various sources, the A-CPX methodology presents some deviation from the theoretical emission. The previous calculations have been done by locating the reception points on a 1 m radius quarter-sphere, but according to the methodology and for the tyre dimensions considered for the simulation, a 2 m radius would be more appropriate. For a 2 m radius, the simulation results for all cases give no deviation between the emitted and calculated emission. However, it would be unfeasible to board the microphones during the test campaign using a configuration of 2 m radius. Therefore, it can be assumed the small deviation, lower than half a decibel, obtained when using as smaller radius.

4. Experimental validation of the methodology

Experimental tests were conducted in order to validate the novel methodology. The test campaign was performed with a 1991 3-door 1.6 Ford Escort vehicle, front-wheel drive car, equipped with Pirelli 175/70 R13 82 T tyres, Fig. 6.

The tests were conducted on a paved road of 675 m length composed of a 20 cm thick subbase of graded aggregate, a 20 cm thick base course of graded aggregate, and a surface course consisting of two layers, 5 cm G-20 and 4 cm S-20 with barren porphyry, and sprayed with prime and tack coats, Fig. 7.

Microphones ¼-inch Bruel & Kajer model 4935 were utilized, connected to the 24 bit 16 channel Pimento data acquisition system (LMS International), operating at a sampling frequency of 25 kHz. The frequency range employed was between 100 Hz and 10 kHz, and the results were presented in one third octave bands, as shown in the next sections. Microphones were calibrated and tested to check their phase, and were protected by windscreens during the test campaign. Weather conditions and road surface temperature were registered periodically.

According to the A-CPX methodology, five microphones were distributed around the tyre under test. Also the traditional CPX positions were included in the set-up: front and rear mandatory positions and middle optional position. Tests were conducted for six reference speeds: 40, 50, 60, 70, 80 and 90 km/h, and three repetitions were performed for each speed, travelling a total distance of 600 m for each speed. The vehicle speedometer and also a GPS, with a sampling frequency of one data per second, were used to control driving speed.

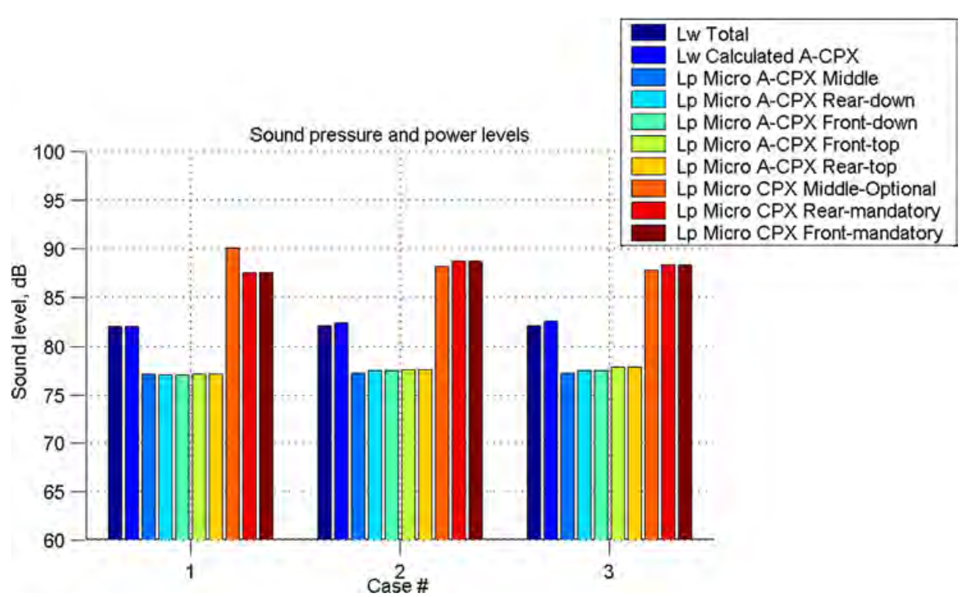

Fig. 5. Sound pressure levels and sound power levels calculated by the algorithm.

Fig. 6. Test vehicle and tyres.

Fig. 7. Detail of road surface over which tests were conducted.

4.1. Early A-CPX tests

In a first test campaign, microphones were attached to the vehicle with two supporting frames specially designed to this function, Fig. 8.

The averaged sound pressure levels for each reference speed recorded during early A-CPX tests (denoted as A-CPX-I) are shown in Fig. 9. Also the sound pressure levels registered at the traditional CPX positions are shown.

Fig. 8. Configuration used in the early A-CPX tests.

Results show the same pattern for positions located in A-CPX and traditional CPX locations: a predominant energy concentration at middle frequencies, between 800 and 1250 Hz, that according to the literature [18,28] corresponds to tyre/road noise emission. That pattern is similar for all speeds and also for all microphone locations, included the traditional CPX ones. As a general trend, an increment of the registered sound pressure levels is linked to the driving speed.

In those curves, a relative maximum peak at lower frequencies (400 Hz for 40 km/h) is also observed. Such peak shifts to the right in the spectrum as speed increases (800 Hz for 80 km/h or 1 kHz for 90 km/h). Noise levels at those frequencies are generated by the impact periodicity of the tyre treadband blocks against the road surface, as the pattern of the test tyre has a tread pitch of 22 mm, Fig. 10. In the Table 3 it is illustrated the impact frequency due to treadband pattern impacts, calculated according to Eq. (8), where f corresponds to the impact frequency (in Hz), v is the driving speed (in m/s) and l is the tread pitch (in m). The frequencies have been calculated according to the actual average driving speed of the vehicle, obtained from the GPS system (it was observed a deviation of 13% from the speedometer speed).

$$f = \frac{v}{l}\,(\mathrm{Hz}) \tag{8}$$

The graphs presented in Fig. 9 have particularly high levels at low frequencies, and they are higher than usual in a common rolling noise spectrum. The behavior of sound levels at those frequencies is close to lineal, presenting a negative slope, since sound levels decrease as frequency increases. The frequency range affected by such behavior increases with the speed: up to 400 Hz at 40 km/h, and up to 630 Hz at 90 km/h.

Fig. 11 shows, per each reference speed, the average sound power level spectrum obtained after processing data according to the A-CPX method. The spectrum also reflects the features of a common tyre/road noise spectrum in the range of medium frequencies, and it also displays the behavior at low frequencies observed in Fig. 9.

It is very usual to find in the literature that tyre/road noise levels are expressed using a logarithmic regression, according to the Eq. (9), as a function of the vehicle speed (v) and defined by two coefficients, A and B. For instance, in [29] it is obtained A = 31.7 dB(A) and B = 33.3 dB(A) in an analysis about the dependence on speed of the rolling noise on a rehabilitated pavement by using the CPX measurement method. The CPX method is also

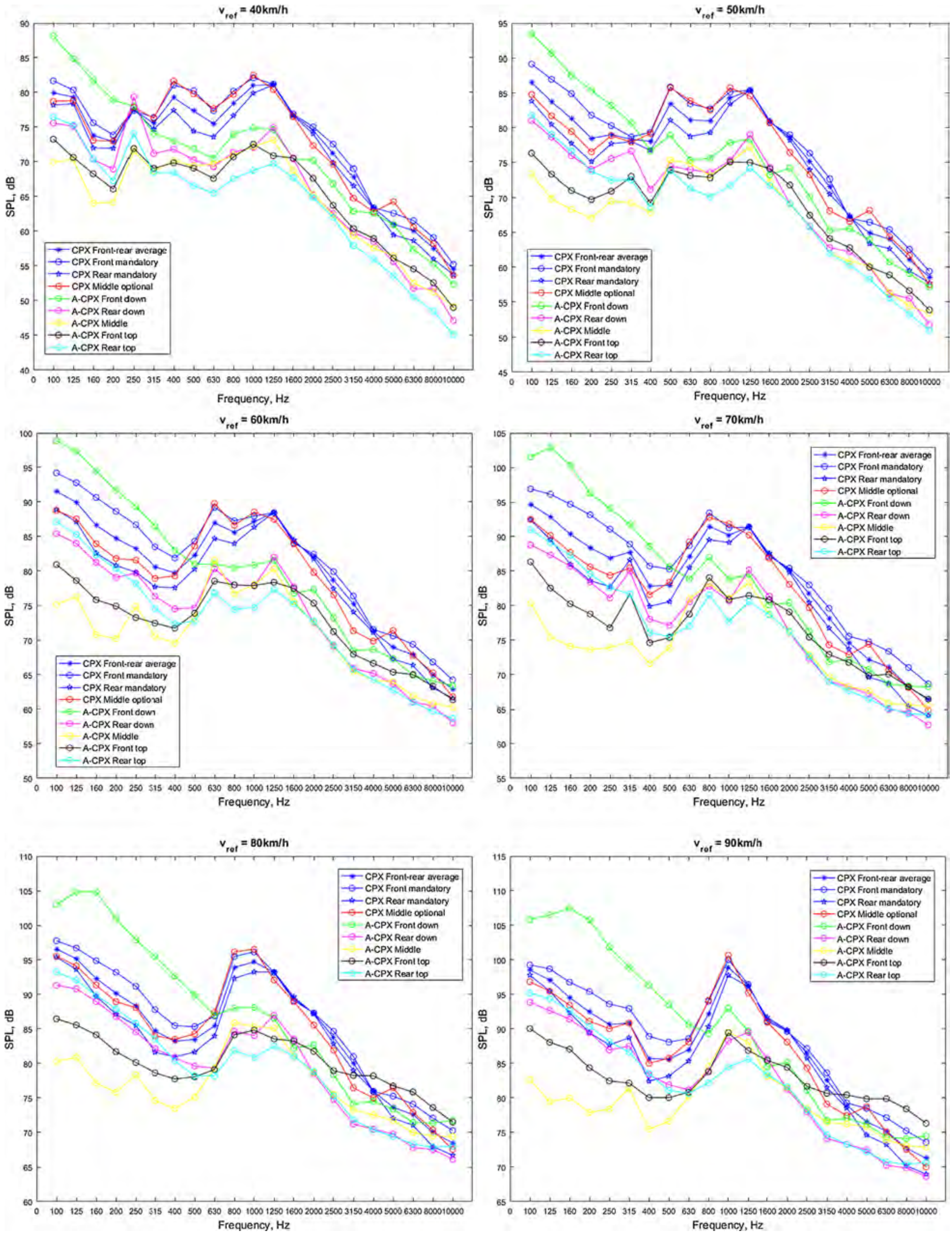

Fig. 9. Average sound pressure level in bands of 1/3rd octave, in dB, early A-CPX tests.

used in [30] to perform a statistical analysis on the tyre/road noise, vehicle speed and acceleration. In that case, the values $A = 38.0$ and $B = 29.5$ were obtained and it is also referred a publication [31] where the coefficients A and B varied from 21.9 to 27.9 and 32.9 to 39.9 respectively. Therefore, from those studies it can be derived that both terms, A and B, adopt positive values in a range about a few tens. This can also be confirmed from [18], where it is collected a summary of the A and B terms from other different tyre/road

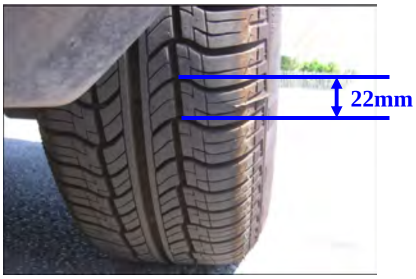

Fig. 10. Test tyre tread pitch.

Table 3
Impact frequency due to treadband periodicity.

Reference speed (km/h)	Actual speed (km/h)	Impact frequency; 22 mm (Hz)	1/3rd octave band center frequency (Hz)
40	34.8	439	400
50	43.5	549	500
60	52.2	659	630
70	60.9	769	800
80	69.6	879	800
90	78.3	989	1000

noise studies, as well as it is analyzed the relation between both coefficients.

The Eq. (10) and Fig. 12 show the broadband sound power levels as a function of speed for the results collected in the present research. As it is observed, the negative value of the independent term *A* is not consistent with the values derived from the literature. Given the results at low frequencies in Figs. 9 and 11, and also the unusual value of the term *A*, it is suspected that the measurements were disturbed in some way during the test campaign.

$$L = A + B \cdot \log(v) \quad (9)$$

$$L_{W\_A-CPX-I} = -4.3 + 59.6 \cdot \log(v)\ (\mathrm{dB}) \quad (10)$$

Wind disturbance is an important factor to have into consideration when measuring tyre/road noise in CPX tests. The effect of wind on the measurement registered by a microphone protected with a windscreen can be found in [32]. From the results of the study it can be extracted that the frequencies below 315 Hz are the most disturbed by aerodynamic noise, and the affected frequency range increases with the wind speed. At high frequencies, above 4 kHz, the measurements also show the wind influence, although the disturbance is not as high as that occurred at low frequencies. A similar conclusion can be derived from [33], where it is observed that the frequencies below 1 kHz are the most affected by wind noise during the CPX test, and it is recommended that CPX measurements should be done when the wind speed is below 15 km/h. According to the conclusions derived from those studies and given the high noise levels at low frequencies showed in Figs. 9 and 11, it suggests that the measurements during the early A-CPX test campaign were affected by wind noise.

As extracted from the literature, the 315–4000 Hz is the frequency range in which microphone recordings are usually less affected by wind noise. Then, a similar expression (11) was obtained for such frequency range.

$$L_{W\_A-CPX-I\ @\ 315-4000\ \mathrm{Hz}} = 4.3 + 50.3 \cdot \log(v)\ (\mathrm{dB}) \quad (11)$$

The resulting term *A* in the equation seems now to be more consistent with those proposed by the literature, which reinforces the hypothesis of wind noise disturbances during the measurements. The frame used for microphones support, which is composed by

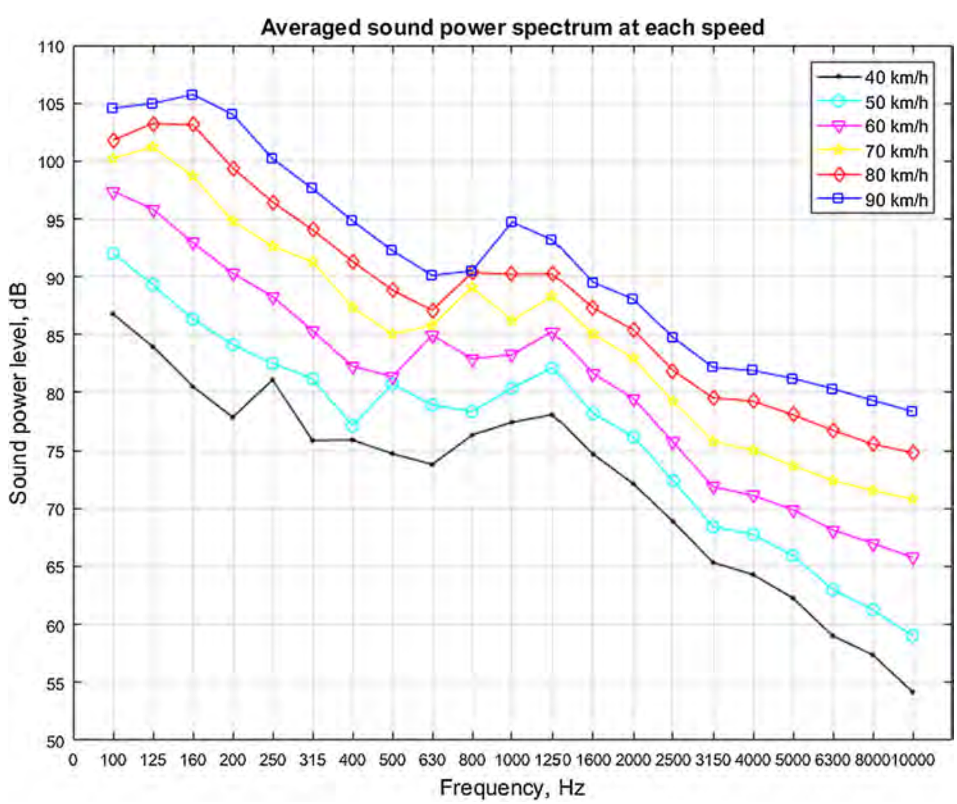

Fig. 11. Average sound power level in bands of 1/3rd octave, in dB, early A-CPX tests.

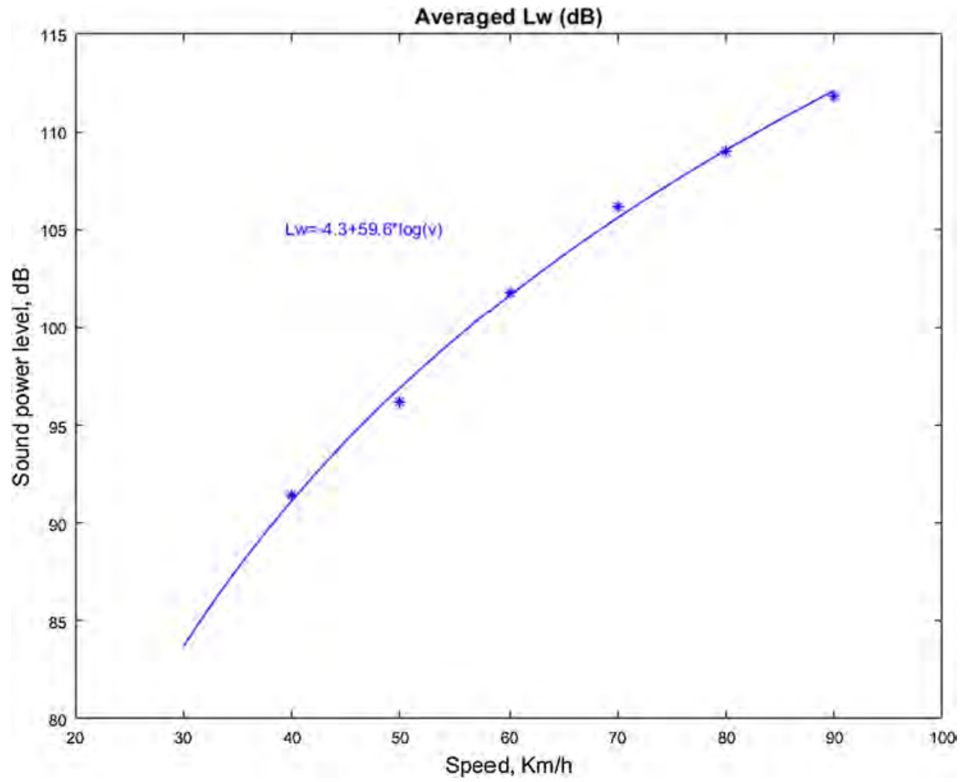

Fig. 12. Sound power level as a logarithmic function of speed, in dB, early A-CPX tests.

square bars, could have contributed to increase wind turbulences around microphones. Some other studies found in the literature describe experimental tests performed with microphones boarded on different types of moving vehicles [34–36] where different solutions to reduce aerodynamic effect have been applied. Hence, a second testing campaign was conducted, using for that purpose an improved supporting system for microphones.

4.2. Final A-CPX tests

The new test campaign (denoted as A-CPX-II) was done under the same conditions as the previous one, but just with the difference of the microphone supporting system. It was employed a set of blades, conventionally used for airplane modeling, Fig. 13.

Fig. 13. Configuration used in the final A-CPX tests.

Fig. 14 exposes the averaged sound power level spectra calculated after processing data recorded during the final A-CPX tests. The spectra are showed for all measured frequencies, i.e. from 100 Hz to 10 kHz. In comparison to the previous results, the spectra of the new results show an important reduction of noise levels at low frequencies, due to the improved aerodynamic behavior during measurements. For low driving speeds, the spectra are only minimally affected by the aerodynamic component. For the highest speeds, which are the most exposed to wind noise, the spectra show the normal behavior of a tyre/road noise for frequencies above 315 Hz. Therefore, these results demonstrate the importance of selecting slender frames for supporting microphones.

As commented before, the range of frequencies affected by wind has been considerably reduced, and the upper frequency affected is 315 Hz for the highest speed. The next step is to calculate the broadband sound power level of the rolling noise. That value was calculated considering the frequency range from 315 Hz to 4 kHz, and it also was expressed as a function of speed, following a logarithmic curve, Eq. (12).

$$L_{W\_A-CPX-II} \quad {}_{@\,315\,-\,4000\,\mathrm{Hz}} = 21.0 + 39.9 \cdot \log(v)\,(\mathrm{dB}) \tag{12.a}$$

$$L_{W\_A-CPX-II} \quad {}_{@\,315\,-\,4000\,\mathrm{Hz}} = 17.0 + 41.9 \cdot \log(v)\,(\mathrm{dB(A)}) \tag{12.b}$$

Finally, to confirm the viability of the final test configuration, the Table 4 collects the sound power levels obtained in early and final tests. The comparison of both results shows that higher the speed, higher the variation between both tests, which indicates that disturbances caused by wind noise have been reduced.

5. Tyre/road sound power level of a moving vehicle

The A-CPX methodology allows the evaluation of the sound power level emitted by a rolling tyre installed on a dead axle, as it has been demonstrated in the previous section. The fact that

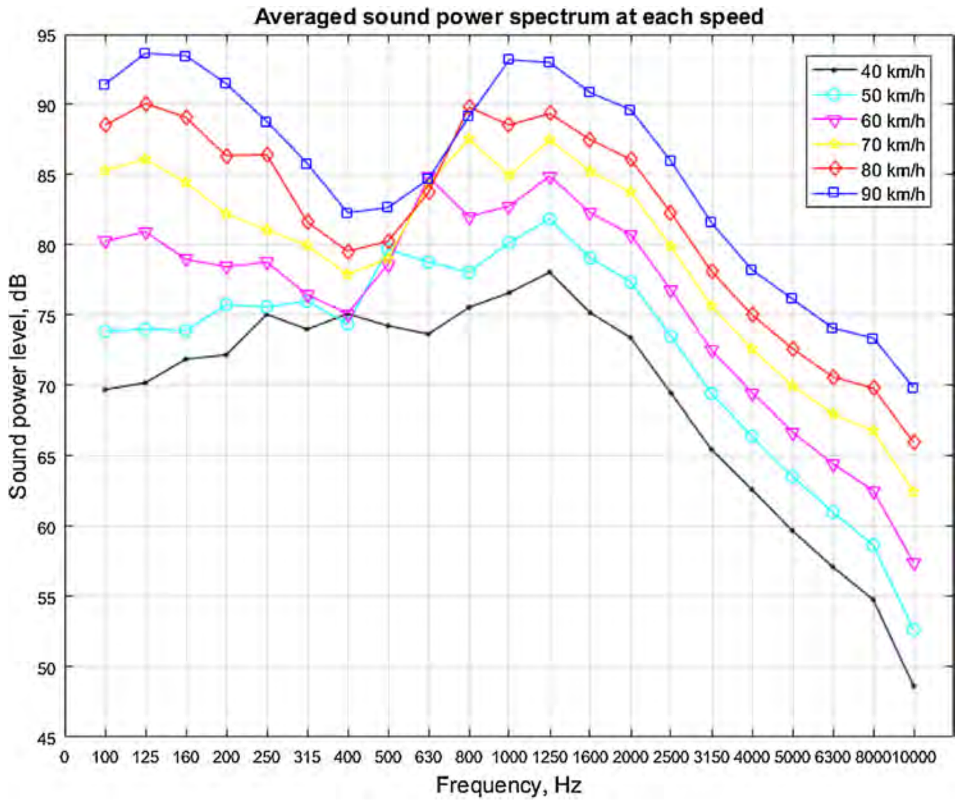

Fig. 14. Average sound power level in bands of 1/3rd octave, in dB, final A-CPX tests.

Table 4
A-CPX Sound power level, overall value.

Reference speed (km/h)	$L_{W\_A\text{-}CPX\text{-}I\ @315\text{–}4000Hz}$ (dB) $L_W = 4.3 + 50.3{\cdot}\log(v)$	$L_{W\_A\text{-}CPX\text{-}II\ @315\text{–}4000Hz}$ (dB) $L_W = 21.0 + 39.9{\cdot}\log(v)$	$(L_{W\_A\text{-}CPX\text{-}I\ @315\text{–}4000Hz}) - (L_{W\_A\text{-}CPX\text{-}II\ @315\text{–}4000Hz})$ (dB)
40	84.9	84.9	0.0
50	89.8	88.8	1.0
60	93.7	91.9	1.8
70	97.1	94.6	2.5
80	100.0	96.9	3.1
90	102.6	99.0	3.6

the tested tyre is installed neither on a drive nor on a steering axle is an important condition for the tyre/road noise emission. As collected in the literature [18], the influence of the torque applied to driven tyres may cause an increase of the tyre/road noise of up to 12 dB or even higher.

In a Coast-By test, the vehicle is in free-rolling, that is, in non-powered operation. That fact entail that the rolling of the tested tyre in an A-CPX test could be compared to the Coast-By conditions in which tyres are running during a Coast-By test. Therefore, the tyre/road noise power level emitted by the whole vehicle, i.e. by the set of tyres of the vehicle, running in Coast-By conditions, could be calculated from the expression obtained for a single tyre in A-CPX conditions. If it is considered that the four tyres on a vehicle running in Coast-By conditions are non-coherent noise sources and all emit the same sound power level, then, the total tyre/road sound power level can be calculated as a logarithmic sum of four sound sources, Eq. (13).

$$L_{W\_TOTAL} = 10 \cdot \log_{10} \sum_{i=1}^{4} 10^{(0.1 \cdot L_{W_i})} = 10 \cdot \log_{10}\left(4 \cdot 10^{0.1 \cdot L_W}\right) \text{ (dB)} \quad (13)$$

The previous expression is applied to Eq. (12) to obtain the total tyre/road sound power level emitted by the vehicle-tyres tested in the previous section, and results on Eq. (14).

$$L_{W\_TOTAL\_A-CPX} = 27.0 + 39.9 \cdot \log(v) \text{ (dB)} \quad (14.a)$$

$$L_{W\_TOTAL\_A-CPX} = 23.0 + 41.9 \cdot \log(v) \text{ (dB(A))} \quad (14.b)$$

The expression (14) can be compared to an analogue expression obtained for a whole vehicle running in Coast-By conditions. In a previous research [37], it was presented a novel procedure, named Alternative Coast-By (A-CB) methodology, to determine sound power level of tyre/road noise of a vehicle running under Coast-By conditions. In that study it was tested the same vehicle-tyres configuration employed for the current research, and as a result it was obtained a logarithmic equation that represents the sound power level of the tyre/road noise of the vehicle.

The A-CB methodology has been reproduced in the current research, with the same vehicle-tyres configuration, and considering the frequency range from 315 Hz to 4 kHz. The expression (15) collects the results of such test.

$$L_{W\_A-CB} = 27.8 + 40.1 \cdot \log(v) \text{ (dB)} \quad (15.a)$$

$$L_{W\_A-CB} = 23.7 + 42.4 \cdot \log(v)\,(\mathrm{dB(A)}) \tag{15.b}$$

It is observed that the terms *A* and *B* in Eqs. (14) and (15) have a strong similarity, and they are the same if the values are rounded to the nearest integer, presenting in such case a small deviation of 1 dB for term *A*. This fact implies that the A-CPX methodology is perfectly feasible for assessing the sound power level of a rolling tyre in close-proximity conditions, as well as for evaluating the tyre/road noise emitted by a vehicle running in Coast-By conditions. Such conclusion also indicates that the behavior of the tyres installed on the car could be understood as a sum of four point noise sources.

6. Conclusions

The work presented in this paper defines a novel methodology, named alternative close-proximity (A-CPX). The method has been designed to assess the sound power level emitted by a rolling tyre installed on a car when it is circulating, by means of sound pressure level measurements. The procedure is based on the traditional Close-Proximity method and also on the guidelines described on the ISO 3744. The main benefit of the method is to provide an alternative magnitude, the sound power level instead of sound pressure level, in order to characterize the noise inherently generated at the tyre/pavement interaction.

A theoretical study, based on different distributions of point noise sources emitting pink noise, has demonstrated the analytical feasibility of the methodology, and very low deviations between the calculated and theoretical emissions were obtained. As a future work, it will be of interest to include the possibility of adding noise sources able to emit sound signals different from the pink noise, so the effect of the asymmetric radiation in a real tyre emission and frequency dependency could be studied. The technical feasibility of the method was tested by experimental measurements. In a first test campaign it was observed an important contribution of aerodynamic noise at low frequencies. Such disturbances were minimized by the adoption of a new test frame to support microphones. It has been finally decided to analyze results in the frequency range of 315–4000 Hz, obtaining a logarithmic expression that relates road/tyre sound power level to vehicle speed. The expression obtained defines the sound power level for the specific vehicle-tyre configuration, and it may vary for different vehicle-tyre configurations.

Finally, the sound power level of the tyre/road noise emitted by the test vehicle has been calculated. It has been assumed as a hypothesis that the four tyres of the vehicle are non-coherent noise sources and all emit the same sound power level. The results have been compared to those obtained after using another methodology, the A-CB methodology, collected in the literature. A very relevant conclusion of such comparison has been obtained: the sound power level of the rolling noise of the whole vehicle when running in Coast-By conditions can be calculated from the energetic sum of the sound power level of an individual tyre installed on a non-driven axle. As a future research, and given that in real driving conditions at least two tyres are powered by the vehicle traction system, it will be of interest to enlarge the study in order to include the effect of the torque on the tyre/road noise emission of the whole vehicle.

Acknowledgements

The work in this paper was partially funded within the framework of the Projects of Scientific Research and Technological Development Bancaja - UMH (RR1522/09).

References

[1] Campello-Vicente H, Peral-Orts R, Campillo-Davo N, Velasco-Sanchez E. The effect of electric vehicles on urban noise maps. Appl Acoust 2017;116:59–64.
[2] International Organisation for Standardization. ISO 13325:2003. Tyres – Coast-by methods for measurement of tyre-to-road sound emission.
[3] International Organisation for Standardization. ISO 11819-2:2017. Acoustics – Measurement of the influence of road surfaces on traffic noise – part 2: the close-proximity method.
[4] Bendtsen, H. Highway noise abatement: planning tools and Danish examples. The Danish Road Institute. REPORT UCPRC-RP-2010-03; 2010.
[5] Kragh J, Andersen B. deciBellA er klar til støjmåling. DANSK VEJTIDSSKRIFT; 2007.
[6] Sainio P, Halén I. Noise measurement trailer HUT NOTRA – means for measuring noise during evolution of road surface. Proceedings of Inter-noise; 2001.
[7] Adams G, Kamst F, Pugh S, Claughton D. Dynamic measurement of tyre/road noise. Proceedings of Acoustics; 2006.
[8] Hung W-T, Kwok M-P, Ng C-F, Wong W-G. The construction of a close proximity trailer to measure road-tyre noise in Hong Kong. Proceedings of Inter-noise; 2006.
[9] Expósito Paje S, Viñuela U, Terán F, López Querol S, Sanz A. Caracterización acústica de diferentes superficies de rodadura en tramos urbanos de Ciudad Real. Proceedings of Tecniacustica; 2006.
[10] Morcillo MA, González JA, Hernández MJ, Hidalgo A. Influencia de la porosidad de los asfaltos en la generación del ruido de rodadura. Coimbra, Portugal: Proceedings of Acústica; 2008.
[11] Freitas E, Paulo JP, Bento Coelho JL. A reduçao no ruído rodoviário com a utilizaçao de pavimentos de baixo ruído. Coimbra, Portugal: Proceedings of Acústica; 2008.
[12] Meiarashi S, Ishida M. Noise reduction characteristics of porous elastic road surfaces. Appl Acoust 1996;47(3):239–50.
[13] Yoshihisa K, Tachibana H. Sound power level measurements for road vehicles by using the square-integrating technique. Proceedings of Internoise 88.
[14] Cho DS, Mun S. Determination of the sound power levels emitted by various vehicles using a novel testing method. Appl Acoust 2008;69(3):185–95.
[15] Peeters B, van Blokland G. The noise emission model for European road traffic. Deliverable 11 of the IMAGINE project, IMA55TR-060821-MP10. January 11th 2007.
[16] Tsukui K, Oshino Y, van Blokland G, Tachibana H. Study of the road traffic noise prediction method applicable to low-noise road surfaces. Acoust Sci Technol 2010;31:102–12.
[17] International Organisation for Standardization. ISO 3744:2010. Acoustics – determination of sound power levels and sound energy levels of noise sources using sound pressure – engineering methods for an essentially free field over a reflecting plane.
[18] Sandberg U, Ejsmont JA. Tyre/road noise reference book. Kisa, Sweden: Informex; 2002.
[19] Iwao K, Yamazaki I. A study on the mechanism of tire/road noise. JSAE Rev 1996;17:139–44.
[20] Ruhala RJ. A study of tire/pavement interaction noise using near-field acoustical holography. Doctoral Thesis. Penn State University; 1999.
[21] Anfosso-Lédée F. Modeling the local propagation effects of tire-road: propagation filter between CPX and CPB measurements. Proceedings of Inter-noise; 2004.
[22] Peeters B, Kuijpers A. The effect of porous road surfaces on radiation and propagation of tyre noise. Proceedings of Acoustics; 2008.
[23] Phillips S, Nelson P, Williams R. Noise testing of tyres. Proceedings of The ITEC Conference; 2001.
[24] Larsson K, Barrelet S, Kropp W. Modeling of tangential contact forces. J Acoust Soc Am 1998;103(5):2920.
[25] Donavan PR, Schumacher RF, Stott JR. Assessment of tire/pavement interaction noise under vehicle passby test conditions using sound intensity measurement methods. J Acoust Soc Am 1998;103(5):2919.
[26] Ruhala RJ, Burroughs CB. Identification of sources of tire/pavement interaction noise. J Acoust Soc Am 1998;103(5):2919.
[27] Ibarra Zárate DI. Contribution of the noise radiated by a single vehicle to the road traffic noise. Doctoral Thesis. Universidad Politecnica de Madrid; 2013.
[28] Sandberg U. The multi-coincidence peak around 1000Hz in tyre/road noise spectra. Proceedings of the Euronoise Conference; 2003.
[29] Paje SE, Luong J, Vázquez VF, Bueno M, Miro R. Road pavement rehabilitation using a binder with a high content of crumb rubber: Influence on noise reduction. Constr Build Mater 2013;47:789–98.
[30] Mak KL, Lee SH, Ho KY, Hung WT. Developing instantaneous tyre/road noise profiles: a note. Transp Res Part D 2011;16:257–9.
[31] Steven H, Pauls H. Entwicklung eines Messverfahrens fur das Reifen-Fahrbahn-Gerausch. Herzogenrath: Report from FIGE; 1990.
[32] Hosier RN, Donavan PR. Microphone windscreen performance. Report NBSIR 79-1599. Washington, DC, USA: Acoustical Engineering Division, National Bureau of Standards; 1979.

[33] Pouliot N, Carter A, Langlois P. Close-proximity measurement of tire-pavement noise on the Ministry of Transportation of Quebec's road network. Proceedings of the Annual Conference of the Transportation Association of Canada; 2006.
[34] Hung WT, Wong WG, Ng CF, Li CW. Comparison of newly devised methods to measure road tire noise. Proceedings of the 9th Conference of Hong Kong Society for Transportation Studies; 2004.
[35] Bracciali A, Ciuffi L, Ciuffi R, Rissone P. Continuous external train noise measurements through an on-board device. Proc Inst Mech Eng, Part F: J Rail Rapid Transit 1994;208(1):23–31.
[36] Anfosso-Lédée F. The development of a new tire-road measurement device in France. Proceedings of the 5th Symposium on Pavement Surface Characteristics – SURF; 2004.
[37] Campillo-Davo N, Peral-Orts R, Velasco-Sanchez E, Campello-Vicente H. An experimental procedure to obtain sound power level of tyre/road noise under Coast-By conditions. Appl Acoust 2013;74:718–27.