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Technical note

An analytical study on the amplification of the tyre rolling noise due to the horn effect

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ABSTRACT

Traffic noise has become an element of stress between economic development and quality of life. For the contact noise between road and tyre, sound sources are located close to the contact path and the tyre-road horn like geometry significantly amplifies the radiated power and its radiation directivity. In this work an analytical method considering the sound diffracted by a sphere placed above a ground surface of finite impedance has been used for the calculation of the horn noise effect. The predicted data has been compared against a set of experimental measurements with the aim of quantifying the accuracy of the model when contrasted with real-time data. This accuracy is fair when excluding the very low and very high frequencies of analysis, that constitutes the horn noise frequency range further emphasised. An application of this procedure is proposed at the end for the estimation of the sound power levels radiated by the rolling sources when circulating in real environments.

1. Introduction

Road traffic noise, univocally related to the economic growth and the demands of the increasing population in urban environments, constitutes one of the main causes of environmental noise pollution. The reduction of vehicle noise sources such as the engine or the exhaust systems in the last decades has been partially masked by increasing rolling noise levels due to the growing trend in the car fleet, and some authors claim that tyre noise is becoming the limiting factor to achieve the imposed noise limitations [1]. Rolling noise is predominant in a typical urban situation when vehicles run smoothly on a road, and is due to the interaction between the tyre and the ground surface. In particular, it is one of the major noise sources for electric or hybrid environmentally friendly urban vehicles. The noise radiation depends on the dynamics of the tyre, the contact between tyre and road and by the influence of the acoustical properties of the ground surface [2]. An exhaustive classification of the tyre dynamic mechanisms can be found in Sandberg and Ejsmont [3], related to radial and tyre sidewall vibrations and deflections that result in air displacements entering or leaving the contact patch.

A horn like geometry is formed within the contact area between the tyre and the road, that is responsible of an amplification mechanism due to the multiple reflections between the tyre belt and the impedance ground [4], increasing the tyre radiation efficiency. In the low and high frequency ranges, the horn is inefficient and the amplification will be low. The frequency range further emphasised is the region between 800 Hz and 2 kHz [5]. The amplified levels may achieve 10–20 dB [4,6,7], but there is a strong dependency on the frequency and on the acoustical properties of the tyre and road surfaces. The horn effect was first explained theoretically by Shaaf and Ronneberger [7] using an image source model that predicted level differences up to 20–25 dB at frequencies between 1 and 3 kHz.

Several 2D models have been proposed first to simplify the real geometry, where the tyre is considered as an infinitely long cylinder. Kropp et al. [1] have developed a model based on a multipole synthesis, where the sound field scattered by the tyre is reproduced by a set of equivalent sources multiplied by unknown coefficients that have to be determined considering the boundary conditions of the problem. This model has also been used by Anfosso-Lédée et al. [6] to study how the absorption on road surfaces could counterbalance the horn amplification effect. The 2D models have been consequently extended to numerical three-dimensional methods. Graf et al. [4] have presented a 3D BEM to carry out parametric studies on how the geometry of the tyre (radius of curvature, load and width, edges) is the key factor that defines broadly the features of the horn effect. They have validated the results against a set of experimental measurements performed in laboratory conditions using the reciprocity principle. Although the frequency range of interest for the horn amplification extends approximately from 500 Hz to 2.5 kHz, these authors have

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presented two asymptotic models in the low and high frequency range, expanding the experimental frequency range of interest [8].

To avoid the use of time-consuming numerical methods, Lui [9] has presented an analytical three-dimensional model to simulate the horn effect based on the sound diffracted by a sphere above a ground surface. They validated their model with an experimental set-up in an anechoic chamber to reproduce conditions of the sound field diffracted by a sphere in free field. This model has been further extended [10] to study the propagation of noise in a horn-like geometry considering impedance road surfaces. By comparison with other published data they concluded that the model gives good results and have presented several parametric studies for the porous road pavement.

Although there exist available data predicted by numerical models or acquired in controlled environments, these results have not been compared against measurement in a real environment under normal driving conditions. Signals acquired according to the standard for Close ProXimity (CPX) measurements [11] are recorded with a microphone mounted on a trailer at a distance of 0.28 m out of the tyre plane, for minimising amplification due to the horn geometry and sound coming from power train and other auxiliary systems. The first purpose of the present work is then to evaluate the accuracy of the analytical models for the simulation of the real horn effect. For that, we will take a set of experimental results carried out in the frame of a project to study how the driving behaviour may have an impact in the reduction of road traffic noise [12].

Most of the models have concentrated on a parametric study for the selection of the optimal properties of the ground surface [5,9,10]. In this work, however, we will apply this formulation for the determination of the sound power levels due to the rolling interaction. To the author's knowledge, this comparison is difficult to find in the specialised literature. Cho and Mun [13] have proposed an experimental method to determine source power levels based on the simultaneous measurement of the near and far-field radiated pressure levels and the assumption of different road surfaces. Considering the same logarithmic relationship established by the Harmonoise algorithm [14], they have adjusted the coefficients by a regression procedure. The originality presented here relies on the derivation of the rolling source power without any assumption on the equations that govern the emitted levels or the need to find the optimal coefficients for different frequency bands.

The rest of the work is organised as follows: the experimental measurements carried out in the near field of the vehicle are summarised first. The analytical model is presented in the next section, and the prediction results are contrasted with other published BEM models and with experimental data. Finally, a methodology based on transfer function inversion is proposed for the estimation of the rolling source sound power. We will finish with the main conclusions and some directions for future work.

2. Near-field measurements

A set of near-field measurements were carried out for the determination of the noise contributions of individual vehicles and the extrapolation to far-field positions [12], situated 7.5 m away. An on-board system was installed on each vehicle for the identification of the drivers responsible for the generation of Maximum Noise Levels (MNL). This system was composed of two microphones located inside the engine hood and close to the right back tyre that provide respectively a measurement of power-train and rolling noise. Due to the requirements of this application, the maximum sound pressure level and the dynamic range of the sensors had to reach 130 dB and 105 dB respectively. A couple of SHURE MX183 electret microphones have been chosen able to fulfil these specifications.

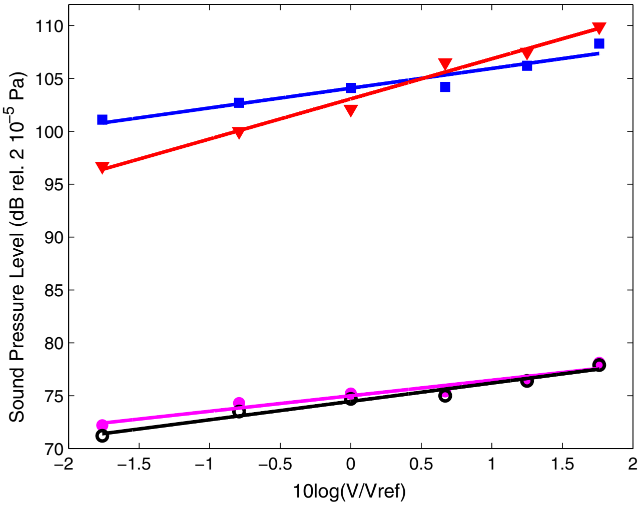

Fig. 1. Pressure Levels-vehicle velocity dependence for the signals acquired close to the engine (blue square), in the proximity of the tyre (red triangle) and at the far-field positions at 1.2 m height (magenta solid circle) and 3 m height (black empty circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Two different sets of measurements were recorded synchronously: the near-field measurements to discriminate the drivers responsible for the generation of the MNL, and the corresponding levels propagated to the far-field positions to evaluate the impact of the vehicle noise on the particular driving behaviour. For this last one, two Fonestar 2214 microphones, protected from the aerodynamic noise by a wind screen, were situated at 7.5 m away from the road edge at two different heights: at 1.2 m in accordance with the standards [11] and at 3 m for comparative purposes.

Several types of light vehicles, that represent 30% of the total Spanish fleet, were tested. The experiments consisted of a set of pass-by measurements made at constant vehicle speed over a straight route in an area isolated from traffic and with low background noise. The measurements were acquired for six different vehicle velocities, starting in 2nd gear at 40 and 50 km/h, progressing to 60 and 70 km/h with the vehicle circulating in 3rd, and finishing in 4th gear at 80 and 90 km/h. They were carried out with overcast sky and atmospheric conditions according to the standards [11], and recorded by the system PULSE LabShop Version 14.0.1 from B&K. An example of the measurements acquired for one course is presented in Fig. 1. We have represented the noise levels for the engine, rolling and far field positions as a function of the ratio V/V_{ref} in logarithmic scale, where V_{ref} has been taken as 60 km/h. Corresponding straight lines have been fitted by linear regressions and are superimposed to the particular measurements values. It can be seen that when increasing the velocity by 10 km/h, the engine noise is increased between 1 and 2 dB and the rolling noise between 2 and 4 dB. This produces an increase of the overall radiated levels to the far-field positions between 1 and 3 dB.

In this work we will use the measurements acquired by the microphone recoding the rolling noise near the front right tyre, Fig. 2, that has been fixed to the surface of the vehicle using a mastic adhesive.

3. Analytical model

Lui [9] hypothesized that the horn effect induced by the semi-closed space formed between the curved surface of a sphere and