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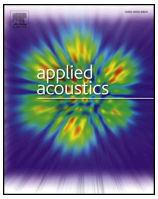

Technical note

Prediction of Close-Proximity Tire-Road Noise from Tire Cavity Noise measurements using a statistical approach

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ABSTRACT

Noise due to the contact between the tire and the road is taking more and more importance in the development of cars, tires, and road coverings. This noise influences the comfort perception of the driver and the living quality of the surrounding people and has to be taken into account during the tire development. A recent study from the Danish Ministry of Infrastructure and Environment estimated that a reduction of the Tire-Road Noise of 6 dB(A) between 2009 and 2020 could save 11 billion euros yearly by reducing the number of annoyed peopled by 13 million and the number of sleep disturbed people by 6 million.

Nowadays, several methods are used to quantify the noise of a rolling tire. All of them are, however, cost- and time-expensive, lack mobility, and are dependent on the surrounding weather and operating conditions. With a self-developed measurement system, it is now possible to predict the emitted Tire-Road Noise by measuring the noise inside the tire cavity.

In this study, reproducible measurements were realized on a tire test bench, where the Tire Cavity Noise and the exterior Tire-Road Noise were simultaneously recorded. The influence of many parameters, such as the driving speed, tire load, inflation pressure, and tire cavity air temperature, on the cavity noise were studied. In the end, a correlation between the Tire Cavity Noise and the exterior Tire-Road Noise was found with a prediction quality of 1.4 dB(A).

This study is a first step towards reducing the time and the costs needed for standard acoustic measurements for tire homologation or for assessing the acoustic quality of different road surfaces. Our measurement method is namely not influenced by the surrounding buildings and can be used without any interference in the flowing traffic. The costs for the needed hardware are also negligible compared to the conventional exterior noise measurement systems. However, the transferability of the results on the tire test rig to field measurements still has to be checked and will be done in a future study.

1. Introduction

The noise emitted by a driving car has become an important and public issue over the past decades. Traffic noise is composed of many noise sources. Among them can be cited motor and powertrain noises, aerodynamic turbulences, noise caused by the exhaust system or brake squealing. However, it was demonstrated in [1] that nowadays, Tire-Road Noise (TiRN) induces the major part of traffic noise not only above 40 km/h, but in all driving conditions. This tendency is going to increase given the growing interest in electro-mobility, and, therefore, the reduction of the acoustic contribution of combustion engines.

Traffic noise has consequences on the appreciation of the living quality near the road [2] but also has an impact on public health. The long-time exposure to traffic noise increases the risk of having cardiovascular diseases [3], hypertension [4] or myocardial infarction [5]. A recent study performed by the Danish Ministry of Infrastructure and Environment estimated the costs savings by reducing the TiRN by 6 dB(A) between 2009 and 2020 [6]. Such a reduction of the TiRN would lead to 13 million less people annoyed and 6 million less people sleep-disturbed by TiRN.

1.1. Relevant work

Nowadays, two methods are mainly used to analyze and quantify TiRN: the Coast-By (CB) method defined in ISO 11819-1 and the Close-Proximity (CPX) method defined in ISO 11819-2.2. Both methods relies on the measurement of exterior noise. However, these methods lack in mobility and require free-field conditions, which are difficult to obtain

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on public roads without road closure and therefore traffic disturbance. In 1981, Bschorr developped a new method to quantify TiRN by measuring the noise inside the tire cavity [7]. Road texture will induce tire vibrations, which can be recorded by the microphone while driving. This Tire Cavity Sound Measurement System (TCSMS) has many advantages compared to the conventional methods. As the microphone is isolated between the rim and the tire, the tire cavity sound measurements are not disturbed by any unwanted noises such as wind, other vehicle noise, or reflection phenomena due to nearby buildings. This means that the measured road does not have to be closed, and the measurement can take place in the flowing traffic.

Tire Cavity Noise has been investigated mainly in order to study the vehicle interior noise such as Sakata in [8]. Thompson [9] developed an analytic model in order to predict the first torus resonance frequency of deflected tires with different tire loads. The influence of the driving speed, the tire cavity temperature and the inflation pressure on the Tire Cavity Noise were studied experimentally by Krauss in [10] by measuring the acceleration at the wheel hub. Bharadwaja showed in [11] that the influence of the tire load and the inflation pressure on the simulated Sound Pressure Level inside the tire cavity SPL_{TCSMS} was not significant. The frequency shift of the torus resonance due to the temperature was analyzed for a static tire by Feng in [12]. Bederna showed in [13] that the torus resonance frequency measured inside the tire cavity do not depend on the speed. If the resonance is measured at the wheel hub, it is split into two peaks due to the rotation of the wheel. This confirms the results presented in [10]. The study of Tire Cavity Noise is also used in the field of road monitoring. Krauss showed in [14] that the influence of the road surface on CPX and TCSMS third-octave band spectra could be detected, giving however no hints on how to correlate both methods with one another. Bschorr also showed in [15] that the transfer function between CB and TCSMS measurements correlated well. However, the study focused on the prediction of a third-octave band spectrum and the prediction quality obtained for an average over different road surfaces was of 4 dB(A) for the third-octave band 1000 Hz. The measurement method showed however excellent reproductibility characteristics with a fluctuation of 0.2 dB over 10 repeated measurements. An automatic classification of the road surface type using specific machine learning algorithms was first found in [16,17]. A first version of this approach was presented in [18].

1.2. Our contribution

The literature up to now mainly focused on the comparison between Tire Cavity Noise and vehicle interior noise. The influence of operating parameters and road surface roughness on the Tire Cavity Noise was either focused on the tire torus resonance frequency or on a qualitative description of their influence on the Tire Cavity Noise. No extensive study was found in order to quantify the influence of operating parameters and of the road surface on the Tire Cavity Noise. This is why we decided to focus this study on two main purposes:

- Quantification of the influence of the operating parameters and the road surface roughness on SPL_{TCSMS}
- Statistical determination of the relationship between SPL_{TCSMS} and the Sound Pressure Level computed according to the CPX method SPL_{CPX}

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In this study, we analyzed the influence of operating parameters such as the driving speed, the tire load, the inflation pressure and the surface roughness on the TCSMS signal of two tires using a full factorial experimentation plan. We measured simultaneously the noise inside the tire cavity and the noise emitted outside the tire according to the CPX method. The influence of the operating parameters and the surface roughness on the Tire Cavity Noise was first analyzed with a statistical model. We then made several statistical analyses to predict SPL_{CPX} from SPL_{TCSMS} based on different driving scenarios. These models can be used in the flowing traffic to efficiently assess the acoustic quality of different road surfaces by making a prediction of the outer noise emission. The relationship between the Tire Cavity Noise and its operating parameters could also be used to predict the road surface roughness by creating a map of the road roughness.

This study is a first step towards an efficient mapping of the road surface acoustic quality. With measurements using the TCSMS on a sufficient amount of different road surfaces, a prediction of the tire rolling noise using the CPX method can be achieved in a much more efficient way than with the CPX or the CB method. Our presented method could be used not only to qualitatively predict the road surface type using classification but to quantify the road surface roughness using multiple linear regression with the MPD as characterizing parameter.

2. Measurement systems and methods

2.1. The inner drum test rig

The inner drum tire test bench consists of a rigid wheel carrying system and a drum with a diameter of 3.8 m. Both the tire (hydraulic) and the drum (electric) can be driven up to 200 km/h, whereby different slip-conditions can be adjusted. With the aid of a hydraulic system, wheel load (up to 15 kN), slip angle (between −20° and 20°) and camber angle (between −10° and 20°) can be varied continuously and independently of each other. Different track segments containing real asphalt or concrete surfaces can also be mounted on the test rig. Since the test bench uses a large inner drum, the influence of the road curvature on the cornering or longitudinal tire stiffness is relatively low compared to an outer drum tire test bench. This curvature influence can be corrected according to a formula presented in [19]. Acoustic panels and acoustic foam are mounted on the test room walls and on the wheel carrying system to prevent noise reflection on the test rig.

2.2. The tire cavity sound measuring system

The data analyzed in this paper were acquired with a self-developed TCSMS [14]. The method and the system are schematized in Fig. 1. The different components building it are described in [16]. The road texture leads to a displacement of the tire carcass, which induces a noise field into the tire torus. As the sound absorption is low, the tire cavity can be

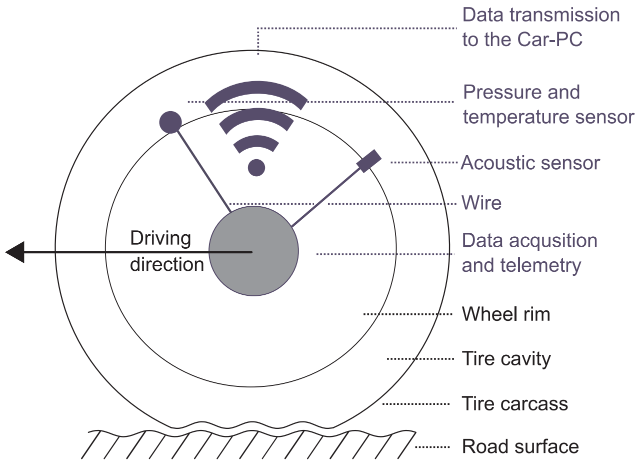

Fig. 1. The acoustic sensor measures the sound pressure inside the tire cavity and additional sensors measure the static pressure and temperature as control variables. The sensors are connected to a data acquisition system attached to the rim flange, which transmits the data to a Car-PC. The tire carcass is excited through the road surface texture, which influences the tire cavity sound, measured with the acoustic sensor. (from [16]).