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An auralization model for structure-borne tire noise

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ABSTRACT

In the automotive industry, a Noise, Vibration, and Harshness (NVH) issue such as road noise is an important factor for the perceived quality of a product. A useful method to address NVH problems and to reduce field-testing is to combine recordings and simulations into auralizations. The objective of this paper was to develop an auralization model of structure-borne tire noise based on operationally measured hub forces and validate it by comparison with artificial head recordings made under the same conditions. To create auralizations under the same condition as the recordings, the wheel hub forces used for the recordings were measured and filtered through experimentally measured binaural transfer functions from the same hub of the car to an artificial head in the cabin of the car. The auralization model was validated in a listening test where the criterion for considering the auralizations to be sufficiently similar to the recordings was that eight different tires should be ranked equally in a listening test regardless of whether the test was based on auralizations or recordings. Listening test results from ranking of tires with respect to the annoyance of interior sounds showed good agreement between auralizations and recordings. There were no significant differences between rankings based on recordings and auralizations – except for tires assessed to be very similar – at either 50 km/h or 70 km/h. The conclusion was that the use of auralizations for ranking of structure-borne tire noise gives results that match listening tests based on recordings, and this supports the validity of the auralization model.

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1. Introduction

In the automotive industry, Noise, Vibration, and Harshness (NVH) issues are important factors for the perceived quality of a product. Interior tire noise is an essential part of NVH. Tire noise is generated from the tire/road interaction and is transferred into the car cabin through structure-borne and airborne paths. At low frequencies, typically less than 500 Hz [1], the structure-borne contribution dominates. Vibrations caused by the tire/road interaction are transferred through the wheel hub to the suspension and chassis and radiate into the car cabin. At higher frequencies, the contribution from airborne tire noise dominates over the structure-borne tire noise. A common method to record and measure interior tire noise is to use an artificial head. The sound is recorded binaurally and can later be reproduced using headphones. This way the spatial information in the sound is preserved [2]. There is always some loss of acoustical cues and spatial information that results in sound deterioration that leads to more difficult source localization [3,4] and separation of sources from reverberation and background noise. However, artificial head recordings are still considered to give valid results when used in listening tests for sound quality assessments.

For both car and tire manufacturers, it is desirable to predict tire noise early in the development process to allow time and cost-efficient product development. This is achieved by moving field-testing to indoor laboratory environments and by using computer-aided engineering tools for early predictions of product performance and qualities. A useful method to address NVH problems and to reduce field-testing is to combine recordings with measurements and/or simulations into auralizations. The required level of detail in the auralization depends on the stage in the development process. In an early development stage, audible errors and artifacts might be acceptable as long as the main character of the sound is realistic. In cases where auralizations are used for detailed psychoacoustic analysis, it is important to keep the auralizations perceptually equivalent to real sounds [5,6]. However, what is considered important for the preservation of a sound's main character might be application specific, but a basic requirement should be that listeners' preference ratings for a certain sound should not be altered due to errors and artifacts in the auralization [7].

Creating accurate interior tire noise auralizations usually requires highly detailed and complex models. Therefore, tire noise

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issues are often handled late in the vehicle development process, and this gives little freedom for modification of the product. The research presented here introduces the possibility of using auralizations of operational hub force measurements filtered through the structure-borne transfer function of a car instead of making artificial head recordings of the same car and tire set up. For a car manufacturer, the number of time-consuming field tests of different sets of tires can thereby be reduced. From the perspective of a tire manufacturer, the number of different cars used in field-testing can be reduced. Commonly, either the car or the tire exists as a prototype or an existing product.

The objective of this study was to develop an auralization model of interior structure-borne tire noise based on operationally measured hub forces and moments in six DOFs (degrees of freedom) and validate it by comparison with artificial head recordings made under the same conditions. The reason for comparing auralizations with artificial head recordings was that this provided a reference to a technique commonly considered to give valid results when used in listening tests for sound quality assessments. By using the same experimental set up for recordings and for measurements of binaural transfer functions (BTFs), the contribution from the set up affected auralizations and recordings equally. However, additional discrepancies will be present in the auralizations due to e.g. errors in the BTFs caused by non-linearities. The criterion for considering the auralization to be valid was that listening tests for annoyance of interior tire noise result in the same ranking of different models of tires irrespective of whether the test was based on auralizations or recordings.

2. Method

For the structure-borne tire noise, the hub acts as the coupling element between the wheel and the car. By measuring forces and moments in six DOFs at the hub, the full structure-borne contribution was obtained. The hub forces served as input to the auralization model and were filtered through experimentally measured BTFs from the hub of the car to an artificial head in the cabin of the car. The output of the auralization model was the interior structure-borne tire noise in the cabin of the car.

In order to validate the auralization model and to create auralizations comparable to artificial head recordings, the same hub forces and measurement set up had to be used for both the binaural recordings and for measuring the BTFs used for creating the auralizations. To determine if different tires would be ranked equally regardless of whether listening tests were based on recordings or auralizations, a selection of various tire types (summer and winter tires) made by different manufacturers and measured at different speeds needed to be included. The measured forces and moments were used to excite the hub of a car where the resulting tire noise was recorded with an artificial head in the cabin of the car. To create auralizations under the same condition as the recordings, the same hub forces used for the recordings were filtered through measured BTFs from the same hub of the car to an artificial head in the cabin of the car. In this case, the same force signals and the same measurement set up were used, and this allowed for a direct comparison. The schematic of the experiment is shown in Fig. 1. The auralization model was considered to be valid if eight different tires were ranked equally in a listening test regardless of whether the test was based on auralizations or recordings.

2.1. Evaluation methodology

To detect small differences in reproduced sounds, pairwise comparison procedures such as the ITU (International Telecommunication Union) recommendation BS.1116-1 have been shown to be an accurate method [8,9]. However, for larger sets of sounds pairwise comparison procedures become time consuming and unmanageable due to the large number of comparisons. In these situations a faster and more efficient method is needed. Ranking procedures – and especially ranking by elimination – have been shown to be a faster approach compared to a pairwise comparison method without any apparent loss of accuracy [10]. Ranking by elimination is based on the idea that one subject at a time is given access to all stimuli and asked to find the stimulus that is considered the most extreme with respect to the assessed attribute (e.g. annoying). When the most extreme stimulus is identified, it is selected and removed. From the remaining stimuli, the procedure is repeated by removing the most extreme stimulus from the remaining stimuli. Eventually, only the stimulus that is considered the least extreme remains. Thus all stimuli will have been ranked in the order they have been eliminated. In this study, annoyance was assessed and the listening test was controlled by the subject through a computer interface as shown in Fig. 2.

2.2. Sound stimuli

2.2.1. Recording the operational hub forces and moments

To determine the extent to which different tires could be distinguished in both recordings and auralizations, the sounds had to cover both larger and smaller audible differences. To cover large differences, studded winter tires, studded winter tires with the studs removed, and a summer tire were recorded. For inclusion of smaller differences, a group of different studded winter tires were used. In total, eight tires were chosen. All tires were premium tires from different manufacturers (Table 1), and all tires had the dimension 205/55 R16 and load index 94.

One tire at a time was mounted on a mobile test trailer. The hub of the trailer was equipped with four 3-component force transducers arranged geometrically to allow estimation of hub forces in six DOFs. The load on the tire was 540 kg, and this corresponded to 80% of the maximum tire load index 94 (670 kg). The trailer was equipped with an air spring suspension. The operational hub forces were recorded on wet asphalt (no rain) at two velocities (50 km/h and 70 km/h) with a sampling frequency of 12.8 kHz.

2.2.2. Measurement set up

Because the hub should be excited by operationally recorded hub forces, no wheel was mounted to the hub. In order to reproduce hub forces and moments, the set up had to be capable of exciting and measuring all six DOFs simultaneously. Inconsistencies due to displacements, alterations, or changes in loading of the structure are thereby prevented. For this study, a medium-sized station wagon was used as the test object. Without a tire or rim mounted on the hub, all equipment was attached directly to the brake disc. A similar set up was used in a previous study where the mechanical mobility of the hub was measured in six DOFs [11].

For a correct reproduction of the moments, the brake disc had to be rigid over the frequency range of interest for structure-borne noise. Because the original brake disc was not rigid over a sufficiently large frequency range, and due to difficulties in loading the suspension and mounting all of the measurement equipment, a special measurement disc was designed and fabricated [11]. With the specially made disc, a mount for adjusting the load of the hub/suspension was made. The measurement disc was made into a square shape to fit the measurement equipment as well as to create evenly spaced excitation points. To excite moments in the self-aligning moment (α-direction) (ISO 8855:2011 [12]), a cantilever beam had to be attached as shown in Fig. 3. The disc was milled from a steel plate and made solid and thicker compared to the original brake disc to increase the frequency range over

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