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The effect of porous road surfaces on radiation and propagation of tyre noise

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It is well-known that porous road surfaces are very effective for the abatement of tyre/road noise. However, the physical principles behind the noise-reducing properties of these surfaces are not well understood and often even misinterpreted. Lack of understanding becomes a problem when developing a prediction model for tyre/road noise to be able to optimize the road surface for noise abatement. In the framework of the EU SILENCE project and the Dutch IPG program a model has been developed to predict the influence of road surface porosity on the radiation and propagation of tyre/road noise. First step in the model development was to gain physical insight from stationary and vehicle measurements with passenger car and truck tyres on both dense and porous surfaces. Next step was to qualitatively and quantitatively describe the observed physical phenomena in a mathematical model according to the KISS principle: avoid unnecessary complexity, both in input parameters and in the mathematical model. The end result is a mathematical model that describes the noise reduction potential for a standard tyre on various (porous) road surfaces, using a sound absorption spectrum as input. This model is available for a broad audience in the recently launched SPERoN acoustic optimization tool.

1 Introduction

SPERoN is a tyre/road noise prediction modelling framework developed over the past decade by a consortium consisting of M+P, Müller-BBM and Chalmers University [1]. SPERoN is an acronym for Statistical Physical Explanation of Rolling Noise. The purpose of the framework is to predict the influence of road properties on tyre/road noise.

SPERoN is a hybrid modelling framework, consisting of physical parts, e.g. for the prediction of the tyre/road contact forces, and statistical parts such as a series of multivariate linear regression models to predict the noise spectrum resulting from tyre vibrations, airflow-related mechanisms, tyre friction, tyre cavity noise and aero-dynamic vehicle noise.

In the last two years the model has been considerably extended and improved within the EU 6th Framework programs SILENCE [2] and ITARI and in the Acoustic Optimization Tool (AOT) project funded by the Dutch Road Directorate. Within this last project, the SPERoN model has become available to a wide public in the form of a GUI-driven software tool.

In the early versions of the SPERoN framework, the road was characterised by its texture and flow resistance. Implicitly, the road was considered to be impervious and without acoustic absorption. However, the noise reduction due to absorption of porous surfaces is very significant. Therefore, an extension has been developed in the SILENCE project to allow the prediction of tyre/road noise on porous, absorptive road surfaces.

This article describes the results of the development of the SPERoN extension for absorptive road surfaces. First, we have experimentally investigated the influence of road absorption on the emitted tyre/road noise. On the basis of these findings, a mathematical model was developed to predict the observed influence. The parameters for this model were obtained from additional rolling noise experiments. Finally the model was validated on a number of porous surfaces with different absorptive characteristics.

2 Sound absorption and the horn effect

The horn effect is the amplification of the sound originating from the tyre/road contact patch due to the geometric (horn-like) shape of the tyre on the road. This horn improves the radiation efficiency for sound waves in the 500 to 2500 Hz range, having wavelengths comparable to the tyre width. Measurements and BEM calculations performed in the SILENCE project have shown an amplification up to 18 dB(A) in the 1 – 2 kHz range, if both tyre and road surfaces are impervious and smooth.

The effect of sound absorption of the road surface on the tyre noise immission is qualitatively known. There are two aspects that play a role in the noise reduction effect of absorptive road surfaces. The largest effect is the reduction of noise amplification by the tyre/road horn geometry. This reduction of the horn effect is due to a decrease of the radiation efficiency when a absorptive surface is present in the horn. A second effect is the partial elimination of sound waves reflected off the road surface in the propagation to the receiver. In practice, it is not obvious how to distinguish between these two effects. Ronneberger demonstrated that it is even possible to consider the amplification of horn effect the result of multiple reflections of sound waves in the horn between tyre tread and road surface [3]. For this reason, we will consider the effect of absorption on the reflected sound as a part of the horn effect reduction.

The horn effect has been studied extensively in the past. Two of the more recent studies were done by Graf [4] and Bécot [5]. These studies provide many insights, but an (experimental) investigation of the horn effect for realistic tyres on realistic porous roads is not available from literature. We therefore developed an experimental setup to study the horn effect under realistic tyre and road conditions. With this setup we investigated the effect of sound absorption on the horn amplification.

Our experimental setup to study the horn effect consists of a tyre mock-up with microphones and an omnidirectional noise source (see Fig. 1). We investigated the sound radiation from 4 sources on the tyre surface to 11 receiver positions in the near field using the reciprocity principle, i.e. we switched the positions of the source and receiver.

Fig. 1 Near-field point source array (left), mock-up with two microphones mounted in the tyre tread (right)

With this experimental setup, a series of stationary measurements has been conducted on several dense and porous asphalt surfaces. Since the exact sound power of the source was not constant over frequency, a miniature microphone was placed in front of the noise source to be able to measure the transfer function from the source to the various microphones inside the tyre.

Measurements with the tyre mock-up were compared to measurements of the transfer functions using the same source and microphone positions on the same surface, but without the tyre. The difference in transfer functions between both situations thus represents the effect of the presence of the tyre, i.e. the horn effect.

A typical result of the horn effect on a dense surface is given in Fig. 2 for microphone positions in the middle of the tyre tread, one at 15 cm circumferential distance from the contact patch centre, the other at 10 cm, i.e. closer to the throat of the horn (see Fig. 1). The noise source was in front of the tyre, aimed right into the horn.

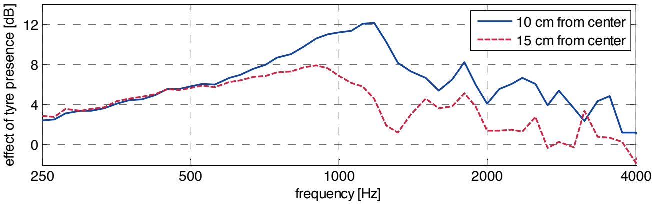

Fig. 2 Difference in transfer functions with and without tyre, on a reflective surface for two tyre source positions

Indeed, the presence of the tyre causes an amplification of up to 12 dB(A) at 1 kHz. In the frequency range above 700 Hz, the effect is smaller for the microphone position further outward, which was also found by using analytical model calculations for an infinite cylinder [6].

If the transfer function measured for a dense non-absorbing surface is subtracted from the transfer functions for several different porous surfaces, having different sound absorption, we obtain the spectrum that describes the influence of the road absorption on the tyre/road noise. To be able to relate this influence to sound absorption properties of the porous roads we have also measured the sound absorption spectra under normal incidence using the ISO 13472-1 Extended Surface Method.

A typical result from such a comparison is given in Fig. 3 (top graph) which shows the difference in the measured transfer function between a dense and two different porous asphalt concrete surfaces. The bottom graph shows the sound absorption spectrum measured on these surfaces. Comparing both spectra reveals a direct relation between the measured sound absorption and the reduction of the horn amplification found on the two porous surfaces. More precisely, we made the following observations:

- the minima in the noise reduction curves are shifted to higher frequencies with respect to the peaks in the absorption spectra, by a factor f_{sh} of about 1,2;
- although the max. sound absorption value is similar for both surfaces, the resulting noise reduction is smaller for the surface with the lowest frequency for the absorption peak (i.e. 70mm PAC);
- the significant sound absorption around 2 kHz and above has only a minor reduction effect;

A frequency shift between normal incidence absorption and noise reduction is also found from calculations with constitutive porous material models [8, 9], when calculating the attenuation of reflected waves under oblique incidence. However, the shift observed in the measurements is larger than the calculated shift from a single reflection. This indicates that multiple reflections may be acting in the sound transfer to the near-field receiver, see § 3.2.

The last two observations can be explained by looking at the horn amplification spectrum in Fig. 2. The horn effect is less strong in the low frequency range since wavelengths are large compared to the width of the tyre. Therefore the reduction of the horn effect due to absorption is also smaller at lower frequencies. At higher frequencies the radiation efficiency of the horn is also smaller, which makes the sound absorption less effective.

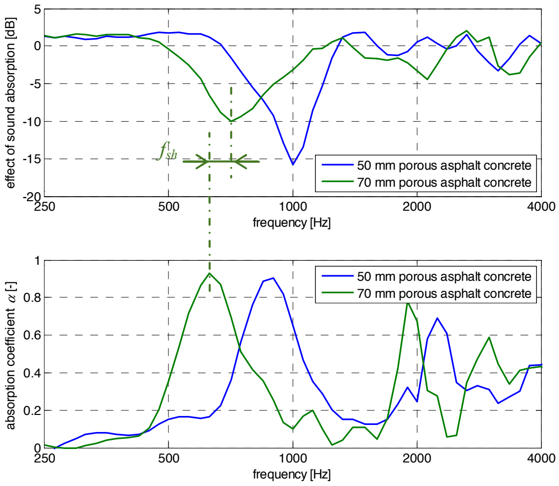

Fig. 3 Effect of absorption on the measured horn amplification for two different PAC surfaces (top), corresponding sound absorption measurements (bottom)

3 The road absorption influence model

3.1 Mathematical description

A mathematical model is needed to decribe the observed phenomena in the SPERoN framework. From the experimental investigation of the horn effect described above, it is obvious to base the quantitative estimation of the noise reduction spectrum directly on the normal incidence sound absorption spectrum of the surface. But in the model we have to take into account a certain amplification factor and a frequency shift.

Hamet [7] proposed a straightforward model to relate normal incidence absorption to noise reduction spectrum:

$$\Delta L_p\left(f\right) = A \cdot \alpha_0\left(f \cdot f_{sh}\right), \qquad (1)$$

with α_0 as the normal incidence absorption, A as the amplitude of the effect and f_{sh} as the frequency shift factor.

Hamet’s model captures the observed frequency shift but fails to describe the reduced effectiveness of the absorption at low and high frequencies. Furthermore, it assumes that the noise reduction scales linearly with the absorption coefficient. In practice we found that that this linear scaling is not valid: surfaces with low to moderate absorption coefficient (i.e. $0{,}2 < \alpha < 0{,}6$) already exhibit a noise reduction effect that is underestimated by using a linear relationship.

To improve the model described by Eq.(1), we propose a new model that deals with these issues. To describe the noise reduction spectrum we use the following expression:

$$\Delta L_p\left(f\right) = \frac{1}{12}\sum_{s=1}^{2}\sum_{r=1}^{6} A_{s,r}\cdot H_{horn,s}\left(f\right)\cdot \alpha_{eff}\left(f\cdot f_{sh,s}\right), \tag{2}$$

where α_{eff} is the "effective" sound absorption spectrum (see § 3.2), shifted in frequency by the f_{sh} factor and multiplied by a (negative) amplification factor A. We assume that the noise reduction spectrum results from a weighted sum of the combined effect for a number of source positions (denoted by index s) and receiver positions (denoted by r).

A frequency weighting H_{horn} was introduced in the model to account for the changed effectiveness of absorption due to the horn effect. This weighting value, which is a value between 0 and 1 as a function of frequency, was based on results from the stationary measurements with the tyre mock-up. The curve results from the measured transfer functions from the two source positions in the middle of the tyre tread to near-field receiver positions 1 to 6 (see Fig. 1 and 4), assuming the horn amplification will be equal to the front and rear.

The amplitude factor $A_{s,r}$ and frequency shift $f_{sh,s}$ depend on both the source and receiver position as was observed in these experiments, e.g. Fig. 2. The calculated attenuation is then averaged over the receiver positions r from 1 (+90°, front) to 6 (0°, side). and over the two source positions s on the tyre tread.

The parameters that remain to be established are the amplitude factors $A_{s,r}$ and the frequency shifts $f_{sh,s}$. We chose to determine these parameters experimentally by using the results from a series of rolling noise measurements. This is explained in section 4.

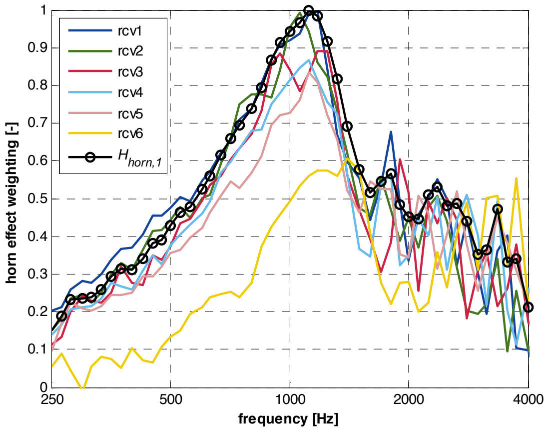

Fig. 4 Measured horn efficiency for $s = 1$, $r = 1..6$ and normalized average horn effect weighting curve $H_{horn,1}$

3.2 Effective absorption coefficient for multiple reflections

Our predictions with Hamet's model revealed the noise reduction was underestimated for surfaces with low to medium absorption, i.e. $0{,}2 < \alpha < 0{,}6$. The prediction results were largely improved by using an "effective" absorption coefficient that is larger than the actual normal incidence absorption coefficient. We defined a relationship between the normal incidence absorption and effective absorption that fitted best with the noise measurements. This relationship is plotted in Fig. 5.

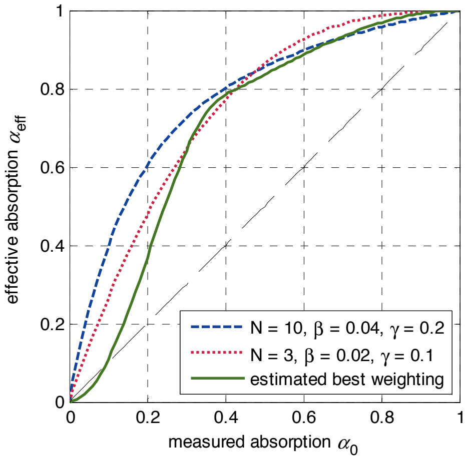

Fig. 5 Relationship between normal incidence absorption and effective absorption.

The rationale behind the use of an effective absorption comes from considering a model of multiple reflections between tyre and road surface, as shown in Fig. 6. From each sound wave reflected on the tyre and road, a fraction α_0 is absorbed by the road. Also, a small fraction β is scattered in the direction of the receiver and thus adds to the total noise level. Finally, a fraction γ is lost by scattering in other directions. Assuming multiple (N) reflections on the road surface explains why the absorption of low absorptive surfaces increases: a low absorption means more sound energy is retained in the reflected wave, therefore the total number of reflections that occurs before all energy is gone is increased. A high absorption means the amplitude of the first reflected wave is almost zero, so there is nothing left to absorb in following reflections.

Because of this multiple reflection phenomenon, the scaling between normal incidence absorption and noise reduction is non-linear. This non-linearity is expressed in our model by using the effective absorption coefficient α_{eff} from the relationship plotted in Fig. 5.

For very low absorption coefficients, i.e. $\alpha_0 < 0.3$, the multiple reflection model was observed to overestimate the absorption effect. This may be explained by the fact that the measured absorption coefficients used for our model development are slightly overrated, since negative values that arise from normal measurement uncertainty are rounded to zero.

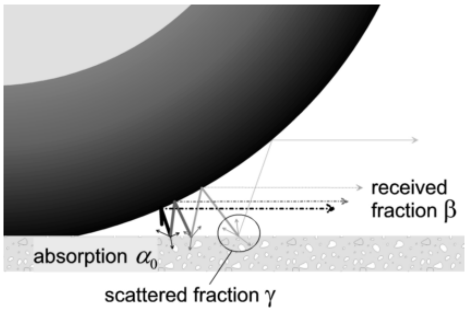

Fig. 6 Multiple reflection model for effective absorption

4 Experimental determination of model parameters

4.1 Rolling noise measurements

In order to fit the absorption influence model to the observed noise reduction effect of porous surface, we used experimental data from the AOT project. Fig. 7 shows the rolling noise measurement trailers that were used to measure the rolling noise of passenger car and truck tyres; 12 types of passenger car and 7 types of truck tyres were measured on 40 different surfaces, over a wide range of vehicle speeds.

Fig. 7 Near-field rolling noise trailers for passenger car tyres (left) and truck tyres (right)

The road surfaces included dense asphalt concrete and SMA surfaces with different textures, as well as 26 porous asphalt surfaces with different layer thickness and stone sizes, covering a wide range of sound absorption characteristics.

A microphone array was mounted on both sides of the trailer, with 11 microphones each surrounding the tyre at different angles from +90° (front) to -90° (rear) with respect to the axle. The standard ISO/CD 11819-2 CPX measurement positions were also included.

4.2 Approximation of sound power levels

Since microphones are placed all around the tyre, most of the sound field radiated by the rolling tyre will be recorded. However, we need a single representative spectral quantity to represent the tyre/road noise for any combination of tyre and road surface, but the exact radiation pattern is unknown. Furthermore, the microphone positions on the array are different for passenger car and truck tyres, so we would like to have a quantity that is also independent of the microphone positions, therefore a simple linear average of sound levels over the microphones does not suffice.

A method has been developed to estimate the sound power levels of a rolling tyre on each surface from the near-field rolling noise measurements. Having the sound power for a particular tyre/road combination allows us to predict in a later stage the sound levels at the receiver positions, for instance those used for CPX or SPB measurements, using any available propagation model.

Fig. 8 shows the 11 positions in the microphone array used for the passenger car tyres. An approximation of the sound power is made by integrating the measured sound pressure levels $L_{p,i}$ over an enclosing surface area.

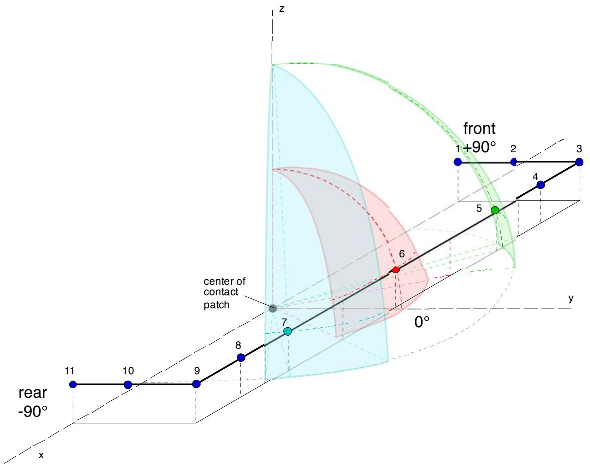

Fig. 8 Sound power is estimated from microphone array by integrating pressure over spherical segments

This area is formed by 11 segments: for each microphone a spherical segment with its midpoint at the centre of the tyre/road contact patch and its radius equal to the radial microphone distance. The segments for pos. 5, 6 and 7 are drawn in Fig. 8. Each segment is bordered by the planes through the midpoint between the microphone and its nearest neighbour, or the x/z plane. The sound power level is found by taking the energetic sum of each sound pressure level multiplied by the segment area S_i:

$$SPL^* = 10\cdot\log_{10}\left(\sum_{i=1}^{11} S_i \cdot 10^{L_{p,i}/10}\right) \qquad (3)$$

This approach assumes that the sound pressure is constant over the segment. However, the microphones are all positioned in one horizontal plane around the tyre. The directivity in the vertical plane is therefore ignored. This means that the quantity obtained should not be mistaken to be the actual sound power level. Nevertheless, it is considered to cover that portion of the sound field that is most relevant for the noise immission at the near- and far-field receivers and can therefore be used in the model.

4.3 Determination of model parameters

The goal of the absorption model is to describe the relation between the measured sound absorption spectrum for each surface and the resulting effect on the average SPL^* of all passenger car or truck tyres, as a function of frequency. We have therefore fitted the parameters $A_{s,r}$ and $f_{sh,s}$ in the absorption model described by Eq.(2) to the rolling noise measurement results for each surface, averaged over all tyres included.

As stated in § 4.1, rolling noise measurements are available for many different porous surfaces with various absorption coefficients, but with different surface texture and flow resistance characteristics as well. To study the horn effect, we can not simply compare the SPL^* of a particular sound absorbing surface to that of an impervious surface since texture and flow resistance will also play a role.

To eliminate the influence of texture and flow resistance, we will use our model to predict differences between two porous surfaces that have the same top layer, and therefore have (approximately) the same flow resistance and surface texture, but with different sound absorption characteristics caused by different bottom layers and/or layer thicknesses.

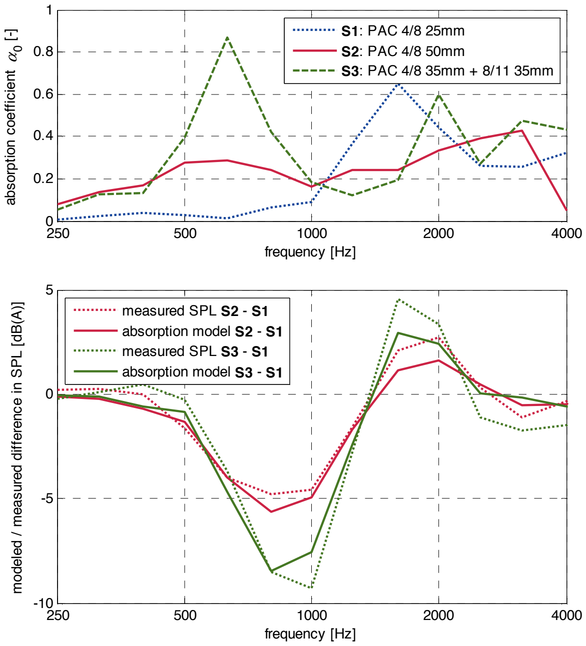

Fig. 9 Measured and modelled difference in SPL: 50mm – 25mm PAC and 70mm DPAC – 25mm PAC (bottom); corresponding absorption spectra (top)

Fig. 9 shows the comparison between three porous surfaces with the same top layer. The top graph shows the measured sound absorption coefficient, while the bottom graph shows the difference in sound power level between surfaces S2 and S1 (red lines) and surface S3 and S1 (green lines). The dotted lines show the difference in SPL determined from the rolling noise measurements, whereas the solid lines show the difference predicted from our absorption model using the measured absorption spectrum as input.

In total, 62 of such surface pairs were available. For each pair, the difference between the total sound power levels (as overall dB(A) value) was determined from the rolling noise measurements. Then, this difference was also calculated using the absorption model. If the absorption model would work perfectly, both calculated differences would be equal. The deviation between model and measurements is given in Fig. 10 below, for each surface pair. The coloured area shows the standard deviation of values around the mean.

In order to show the improvement made by including the effective sound absorption in our model, both the linear absorption α_0 and the effective absorption α_{eff} were used for the model calculations. It is clear from the figure that the latter significantly improves the results.

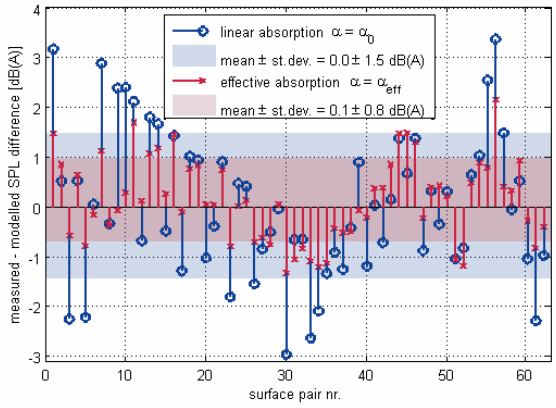

Fig. 10 Difference between modelled and measured SPL differences for each pair of two surface with same top layer

5 Conclusions and recommendations

A model has been developed for predicting the effect of absorption on the tyre/road noise on a porous surface, as a function of the sound absorption spectrum. The model takes into account an upward frequency shift of the noise reduction with respect to the absorption spectrum. It was shown that the model is significantly improved if a multiple reflection approach is used, increasing the effectiveness of sound absorption for low absorption surfaces.

The model parameters have been based on an estimation of the sound power level from a large series of rolling noise measurements. The influence of texture and flow resistance was eliminated by comparing measurement results of surfaces with similar top layer properties.

The model is able to predict differences in absorption effect between two surfaces within 0,8 dB(A) standard uncertainty, including errors in the measurement of the absorption coefficient.

We were not yet able to perform an objective validation of our model using external data. Since these data are scarcely available: test surfaces should have equal surface texture and flow resistance properties. Some useful measurement results on comparable surfaces will become available later this year.

Missing in the model is the propagation of sound power to the receiver positions, since the SPERoN framework aims to predict CPX and SPB levels. Development of this propagation model, including any additional effect of sound absorption, is underway.

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