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**Noise**

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**2aNSa8. Improving the acoustic performance of low noise road surfaces using resonators**

**Manuel Maennel\*, Jens Forssén and Bart Van der Aa**

**\*Corresponding author's address: Mueller-BBM, Munich, 80805, Bavaria, Germany, [manuel.maennel@muellerbbm.de](mailto:manuel.maennel@muellerbbm.de)**

Road surfaces made of porous asphalt are widely used to reduce the tire-road-noise generated during the rolling process of passenger cars and trucks. As the engine noise was reduced significantly in the last decades the tire-road-noise is the main sound source for driving speeds of 40 kmph (25 mph) and higher for passenger cars. This means that low noise road surfaces may not only be used on highways but also on inner-city main roads to generate a significant reduction on traffic noise. However, the acoustic performance of road surfaces made of porous asphalt is limited as a result of the trade-off between acoustic properties and road surface durability. By including resonators e.g. of Helmholtz type in the porous road surface it is possible to improve its absorbing performance without loss in durability. The paper describes recent research activities on such resonators in porous road surfaces made in the European project HOSANNA. The acoustic properties in terms of insertion loss have been calculated for different arrays of resonators. Measurements on realized porous road surfaces including resonators were carried out. The results show that resonators can improve the acoustic performance of porous road surfaces substantially.

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## INTRODUCTION

Noise pollution is a major environmental problem within well-developed industrial countries and emerging nations respectively. The social costs of traffic noise have been estimated to 0.4% of total GDP e.g. for the European Union while the main source of traffic noise is the road traffic. At the same time road traffic is expected to steadily increase, the source strength is not expected to significantly decrease within the near future and the urbanization is still an ongoing process. To reduce the outdoor traffic noise to a sufficiently low level for a good acoustic environment is a major issue of high need.

In urban areas it is however challenging to find suitable methods and measures to reduce traffic noise not only inside residential houses but also on the outside areas such as gardens, parks and playgrounds. It is often not possible to achieve significant positive effects by traffic relocations and acoustic measures like noise barriers are often not applicable in high-density areas. For these reasons low noise road surfaces were developed, which are already in practical use on inner-city and rural roads.

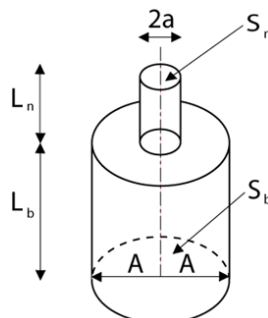
Low-noise road surfaces can be built as dense surfaces with small grain sizes and a smooth texture to reduce the tire-vibrations if there are mainly passenger cars driving on the road. As soon as there are at least small trucks driving on a road the only way to create significant noise reduction with a road surface is to use porous asphalt. Such porous asphalts have void contents between 20 % and 28 % and show e.g. with a layer thickness of 7 cm prominent sound absorption maxima at approximately 600 Hz and 1800 Hz but only low absorption in between these maxima. Buried resonators can now be used as an additional absorber being tuned to the frequency range where the porous asphalt does not show a good absorption (i.e. between the maxima). Which such resonators it is possible to create a more broad-band absorbing road surface being tuned better to the tire-road noise to be damped.

A benefit of using buried resonators is that they can be made to work without impairing the access to the surface. Passenger cars and trucks can drive on porous asphalt with integrated resonators and pedestrians could walk across surfaces with buried resonators. In addition to issues of access as well as aesthetics, the treatments of the road surface or the ground surface are beneficial in terms of their lesser sensitivity to wind. This is in contrast to measures using traditional noise barriers, which may experience severe reduction in performance in downwind condition.

## HELMHOLTZ RESONATORS

### Basic Principles

A single Helmholtz resonator basically consists of a closed volume,  $V_b$ , of arbitrary shape, which is connected to the neck with an opening area,  $S_n$ , see Figure 1. The top neck-opening works as a port through which the resonator communicates with the external medium, here assumed to be a homogeneous non-moving atmosphere. A plug of air enclosed in the neck of the resonator will move downwards after a positive pressure pulse is impinging on the resonator opening and will increase the pressure inside the resonator volume. It is, however, important to realize that the resonators neck is small with respect to the acoustic wavelength of interest, both in length and width. Hence the neck particle velocity along the neck can be assumed to be constant. Also the body dimensions are assumed small in comparison with the wavelength.



**FIGURE 1.** Representation of a single cylindrical Helmholtz resonator. Here,  $L_n$  is uncorrected length of the neck,  $L_b$  is length of the body,  $A$  is radius of the body,  $a$  is radius of the neck opening,  $S_n$  is opening surface area and  $S_b$  surface area of body at opening.

A Helmholtz resonator is a simple spring-mass-system where the air in the neck represents the mass and the enclosed air in the volume represents the spring. To calculate the resonance frequency correctly it is necessary to add the mass of the air directly connected at both ends of the neck to the oscillating mass of air in the neck. The resonance frequency  $f_r$  of a Helmholtz resonator can then be described by

$$f_r = \frac{c}{2\pi} \sqrt{\frac{S_n}{V_b \cdot (L_n + L_{corr})}} \quad (1)$$

where  $L_{corr}$  is the correction for the connected air at both ends of the neck. The neck-correction  $L_{corr}$  is very well described in literature (e.g. in [1] and [2]) for different shapes of the neck and geometrical setups, like e.g.

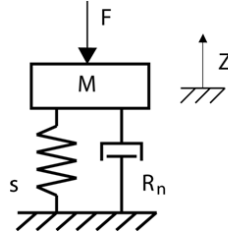
$$L_{corr} = a \frac{8}{3\pi} \left[ 1 - \frac{2}{15} k_0 a + \frac{8}{525} (k_0 a)^2 \right] \quad (2)$$

for a cylindrical neck opening in an infinite wall, or

$$L_{corr} = a \frac{2}{3\pi} \left[ \beta + \frac{1 - (1 + \beta^2)^{3/2}}{\beta^2} \right] + \frac{2}{\pi} \left[ \frac{1}{\beta} \ln(\beta + \sqrt{1 + \beta^2}) + \ln\left(\frac{1}{\beta} (1 + \sqrt{1 + \beta^2})\right) \right] \quad (3)$$

for a rectangular neck opening in an infinite wall where  $a$  and  $b$  are the sides of the rectangle and  $\beta = a/b \leq 1$ .

To calculate the impedance of a Helmholtz resonator the approach proposed by Rayleigh seems here a logical choice since an incoming pressure eventually results in a velocity of the piston, i.e. the air of the neck opening. The piston velocity, which is dependent on the resonator characteristics, can be seen as the speed at which the opening surface  $S_n$  moves due to an incoming pressure. The impedance of the resonating absorber is constituted by its mass, spring-stiffness and resistance. Using a lumped element model makes it possible to visualize the working system by a few simple elements, see figure 2.



**FIGURE 2.** Lumped element model of a Helmholtz resonator excited by a force,  $F$ . Furthermore,  $M$  represents the total mass including end correction,  $s$  the spring stiffness and  $R_n$  the resistance in the neck.

As displayed in figure 2, the upward displacement is defined as positive and the force,  $F$ , is defined in the opposite direction. A force balance results in

$$-F = M a + R_n v + s z \quad (4)$$

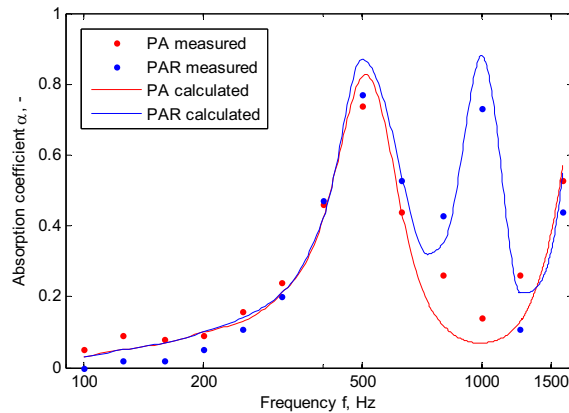
where  $a$  is the acceleration and  $v$  is the speed in the same direction as  $z$ .

The partial differential equation (Eq. 4) is solved using a frequency domain approach, with  $v = j\omega z$  and  $a = j\omega v$ . The impedance,  $Z$ , relating pressure and velocity at a common point, can here be written  $Z = -p/v$ . Using  $p = F/S_n$  gives the impedance as

$$Z_{hr} = \frac{-F}{S_n v} = \frac{j\omega M + R_n - \frac{j}{\omega} s}{S_n} \quad (5)$$

## Calculation of the Absorption Coefficient of Helmholtz Resonators in Combination with Porous Media

A straightforward way of calculating a combined medium of porous asphalt with resonators is to use an empirical [3] or phenomenological [4] model for the calculation of the impedance of the porous media and to change the hard layer on the back by a finite impedance characterizing the impedance of the resonators. It shows up, that the use of a phenomenological model works much better as the finite impedance can be used directly as back layer while an empirical model is not as versatile and correct. Figure 3 shows the comparison of measured and calculated absorption coefficients using the phenomenological model. The measurements were performed according to ISO 10534-2 [5].



**FIGURE 3.** Comparison of measured and calculated absorption coefficients for normal sound incidence. PA: porous asphalt; PAR: porous asphalt with resonators.

The fit between the measurements and the calculations is obviously rather good for both the porous asphalt and the porous asphalt including resonators. The differences in the area of the absorption maximum produced by the Helmholtz resonator (at 1 kHz) can be explained by the applied length correction  $L_{\text{corr}}$ . For buried resonators the air at the outer end of the neck of the resonator is affected by the porous material. The porous material closes parts of the resonator opening and changes therefore the mass of air that oscillates together with the mass in in the neck. This effect was investigated thoroughly in the HOSANNA project and is supposed to be one of the issues with the biggest potential concerning further development of the acoustic performance of buried resonators. For the practical use the outer neck opening of the resonators has to be approximately 20 % larger with respect to the partial closing due to the material of the porous asphalt.

## CALCULATION OF THE INSERTION LOSS

A model has been developed, where the radiation from the openings of the resonators are modeled as auxiliary monopole point sources in an acoustically hard plane. For an original omnidirectional point source, simulating a tire-road noise source, the sound field can be calculated in any point above the plane, after first determining the source strengths of the auxiliary sources, as is briefly described below.

For a set of  $N$  resonators, an equation system needs to be set up and solved. With  $\mathbf{A}$  being a matrix of size  $N \times N$ ,  $\mathbf{q}$  a vector of length  $N$  of the unknown source strengths,  $q_i$ , and  $\mathbf{p}$  a vector of length  $N$  of the incoming pressure from the original source to each resonator opening, the equation system can be written as

$$\mathbf{A} \times \mathbf{q} = \mathbf{p} \quad (6)$$

where elements  $a_{ij}$  of  $\mathbf{A}$  contain the transfer functions from resonator  $i$  to resonator  $j$ .

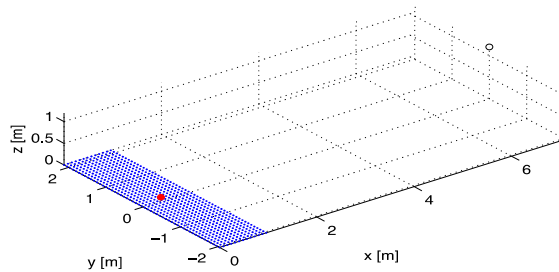
Gaussian elimination can be used to solve the equation system, resulting in the resonator amplitudes  $\mathbf{q}$ , which are used to calculate the total pressure at the receiver as:

$$p(x, y, z) = q[G(r_d) + G(r_r)] + \sum_{i=1}^N q_i G(r_i) \quad (7)$$

where  $q$  is the strength of the original source and  $G(r)$  is the Green function for a point source in a three-dimensional unbounded space  $r_d$  and  $r_r$  are the direct and the ground reflected path lengths from the original source to the receiver and  $r_i$  is the distance from resonator  $i$  to the receiver. The insertion loss at a certain frequency is then calculated as

$$IL = 10 \log_{10} \frac{q[G(r_d) + G(r_r)]}{q[G(r_d) + G(r_r)] + \sum_{i=1}^N q_i G(r_i)} \quad (8)$$

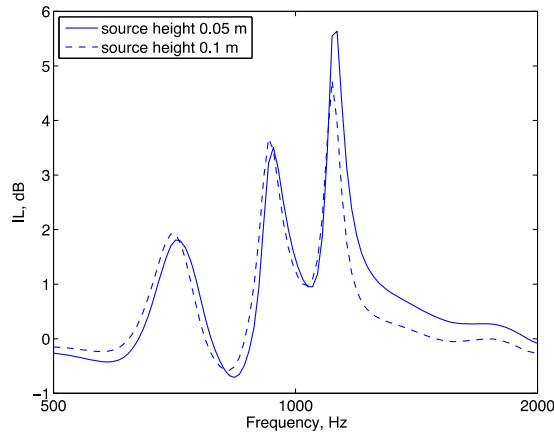
We here attempt to approximately predict the effect of a field of resonators, buried in a porous asphalt layer, on the insertion loss of passenger car tire-road noise, following a real-life test case that is described further below. The predicted results are compared with those of controlled coast by-measurements (i.e. with engine turned off) on a porous asphalt surface with and without resonators, on the basis of ISO 11819-1 [8]. The horizontal distance,  $L$ , from the centerline of the driving lane to the receiver is 7.5 m, the receiver height is 1.2 m and the driving speed is 100 km/h. Having two driving lanes, each 2 m wide, two different cases are investigated: a *near-lane* case and a *far-lane* case. In the *far-lane* case, the sound from the tire-road sources propagates also over the *near-lane*, whereby a larger insertion loss due to the resonators is expected. The tire-road noise from a single passenger car is here modeled using two omnidirectional sources with equal power, at horizontal distances  $L-B$  and  $L+B$  from the receiver, where  $2B = 1.5$  m is the approximate width of the track (gauge). In order to limit the computational cost, the area covered by resonators is limited in space (see figure 4). Toward the receiver, resonators are placed all the way to the edge of the road, whereas in the opposite direction (negative  $x$ -direction in figure 4) resonators are placed only up to a distance of 0.3 m, i.e. approximately a Fresnel zone at 500 Hz, whereby it is reasonable that a resonator influence at around 1 kHz is covered. Along the road ( $y$ -direction in figure 4) a similar reasoning leads to a  $\pm 2$  m coverage of resonators being sufficient.



**FIGURE 4.** Modeling geometry for a single original source (red filled circle), resonators (blue dots) and receiver (black open circle) for the source nearest to the receiver, for the *near-lane* case.

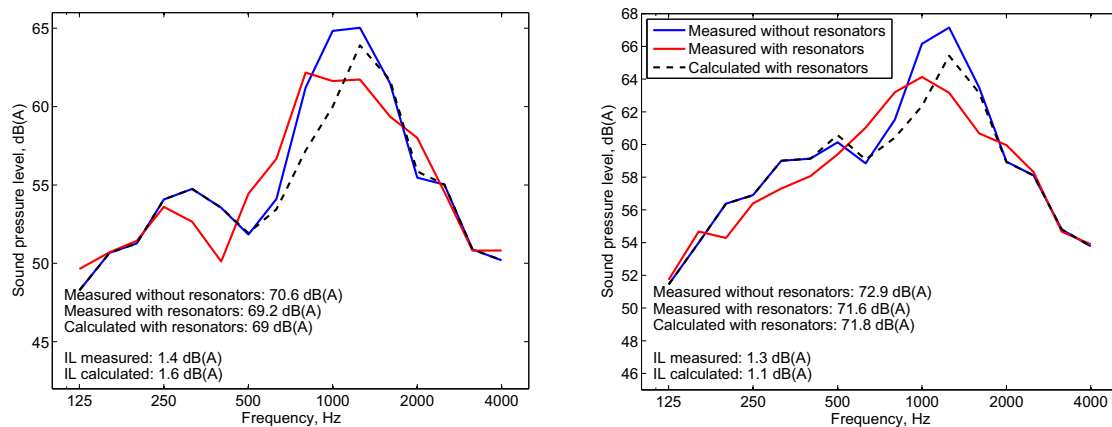
Two source heights, of 5 cm and 10 cm, have been used in the modeling, and the resulting sound pressures have been energy averaged. This somewhat higher position of the effective source than what is usually assumed is motivated by the geometry of the real-life case, where the resonator blocks start circa 45 mm below the surface of the porous asphalt (see figures 7 and 8 below). For the situation depicted in figure 4, the calculated narrow-band insertion loss is shown in figure 5. In order to follow the real-life case, there are 156 resonators per  $\text{m}^2$ ; every sixth resonator having a resonance frequency of 730 Hz, every third 910 Hz and every second 1110 Hz. The resonance frequencies are estimated following Eq. (1) with volumes  $33 \text{ cm}^3$ ,  $17 \text{ cm}^3$  and  $9.5 \text{ cm}^3$ ; opening areas  $1.86 \text{ cm}^2$ ,  $1.41 \text{ cm}^2$  and  $1.13 \text{ cm}^2$ , respectively, and neck lengths of 2 cm, from which the corresponding mass and stiffness terms are estimated. Furthermore, the resistance due to viscous friction is added (following reference [2]). However,

it has turned out that the real losses of the system are larger, probably due to the porous asphalt surrounding the resonator openings. To approximate this effect, an absorbing material is modeled in the neck of the resonators, with a specific airflow resistance of 100 Pa s/m<sup>2</sup> and a thickness of 1 cm (see [2]). The calculations are carried out within the frequency range 500 Hz – 2000 Hz, using a high frequency resolution (one hundred logarithmically spaced points). Furthermore, the modeled resonators are set in a square pattern, for simplicity. As can be seen in figure 5, the effect of the resonators is peaking at the individual resonance frequencies with a fairly damped behavior. It can also be seen that the results are not very sensitive to the modeled source height.



**FIGURE 5.** Calculated insertion loss for a single tire-road source at heights of 5 cm (solid line) and 10 cm (dashed line).

Taking the levels measured without resonators as starting point, the calculated insertion losses are used to estimate the levels with resonators. The measured levels, given in third-octave bands between 125 Hz and 4000 Hz, are assumed constant within each band, whereas the variation of the calculated insertion loss is taken into account within each band. The measured and predicted levels are plotted in figure 6. Considering the spectral shape, the agreement is fairly good, while considering the the total insertion losses (1.4 dB(A) versus 1.6 dB(A) for the *far-lane* case and 1.3 dB(A) versus 1.1 dB(A) for the *near-lane* case), the agreement is good. However, the total size of the insertion loss is rather small, which is due to the specific tire used for the controlled coast-by measurement (Vredestein Snow Track); a larger insertion loss is demonstrated for a statistical pass-by measurement, as shown below (see figure 9).



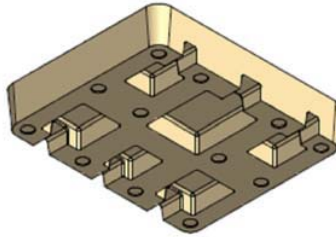
**FIGURE 6.** Measured data and calculated results, shown as A-weighted sound pressure levels, for the *far-lane* case (left) and the *near-lane* case (right).

## PRACTICAL REALIZATION

For the practical realization of buried resonators under porous asphalt it is necessary not only to cope with the acoustical problems but also to understand the requirements from the materials science and constructions point of view. Major parts of this practical work have been done in the preceding German project “Quiet Road Traffic 2” [6]. A road surface and its bedding layers have to resist mechanical, thermal and chemical stresses, they must be easily being laid down and very cost-effective. As material for the resonators polymer concrete seemed to be the best choice. This material is normally used for sewage ducts in the road building industry and shows good material properties for the intended road building purposes.

From the acoustical point of view a combination of three types of Helmholtz resonators (with the resonance frequencies 700 Hz, 900 Hz and 1100 Hz) fitted best into the gap between the two first maxima of the porous asphalt being at approximately 600 Hz and 1800 Hz (keeping in mind that the maximum of the A-weighted road traffic noise spectrum is at about 1 kHz).

The three types of Helmholtz resonators were put together in small resonator arrays in the form of flat bricks made of polymer concrete. The opening of the resonators lies at the side of the bricks so that they cannot fill with drained rain water. A sketch of a resonator array is shown in figure 7.



**FIGURE 7.** Sketch of a resonator array, bottom view.

The resonator arrays are glued to the bedding layer of the porous asphalt (i.e. gussasphalt) with bitumen. The single resonator arrays were laid down with a defined spacing to each other so that the covering porous asphalt can reach the bedding layer and the resonators can communicate with the external air via the void matrix of the porous asphalt. Pictures of the laying process are shown in figure 8.



**FIGURE 8.** Pictures of the laying process.

## ON SITE MEASUREMENTS

A first test track of porous asphalt with resonators on a public road was laid down in Summer 2009 as a demonstrator of the German project “Quiet road traffic 2” mentioned above. This test track was investigated in the recent EC project HOSANNA.

Determining the long term performance of this first generation of resonators is fundamental in order to be able to plan future improvements of the resonators. In the recent measurement campaign near-field measurements of the tire-road noise according to ISO/CD 3<sup>rd</sup> 11819-2 [7] and far-field measurements according to ISO 11919-1 [8] were performed. These measurements were combined with recordings with an artificial head and an ambisonic microphone. The measurements were performed on the track with porous asphalt being improved by the resonators and on a reference test section adjacent to the resonator track made of porous asphalt in the same layer thickness and being as well built in summer 2009. Figure 9 shows the measurement setup and the results of the pass-by measurements.

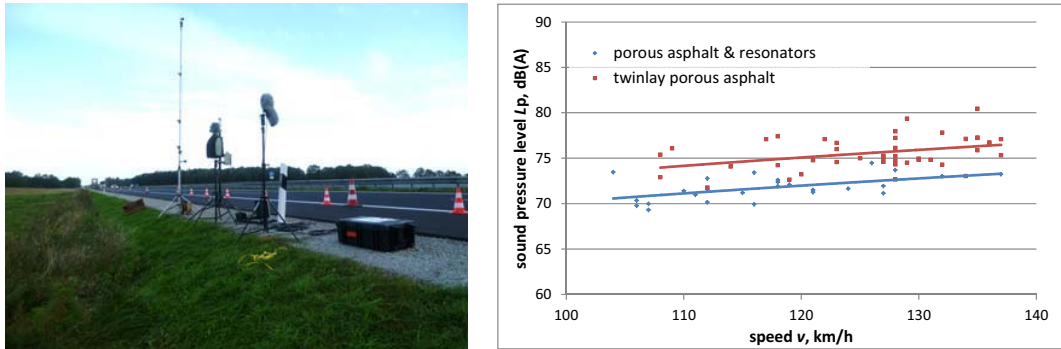


FIGURE 9. Measurement setup (left) and measurement results (right).

In the diagram on the right the sound pressure level is plotted for individual cars over their driving speed (one dot per car) according to ISO 11819-1. It can be seen, that the porous asphalt with resonators shows circa 3 dB lower sound pressure levels than the reference porous asphalt. The level difference in the near field measurements was, however smaller (only 1 dB). This means, that the main effect of the resonators is expected to be due to the reduction during the propagation path over the porous asphalt with buried resonators.

## CONCLUSIONS

The effect of buried Helmholtz resonators was modeled with regard to the perpendicular sound absorption as well as the insertion loss for a field case. Measurements on a test track of porous asphalt with buried resonators were performed. The comparison of measurement data and results derived by the models show a good agreement.

It becomes apparent that buried resonators are an effective measure to increase the insertion loss of porous asphalt. Statistical pass-by measurements have shown that the insertion loss increases by 3 dB compared to a twinlayered porous asphalt. On a section with porous asphalt and buried resonators it was shown that the acoustic long term performance of the resonators is good.

The models being used give the possibility to optimize the resonator design so that the additional 3 dB of insertion loss may be increased for future road building projects.

## ACKNOWLEDGEMENTS

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