

The influence of tyre cavity resonances on the exterior noise

Wolfgang KROPP⁽¹⁾

⁽¹⁾Chalmers University of Technology, Sweden, Wolfgang.Kropp@chalmers.se

Abstract

Rolling noise due to tyre/road interaction is mostly explained by tyre vibrations. The contribution of air-pumping might be an important contributor for certain cases. This observation has often been based on evaluating the speed exponent observed in measurements of the radiated sound. However simulations show that in many cases the observed speed exponent can be explained by tyre vibrations. In addition simulation show that for rough roads the resonances in the tyre cavity can play an important role. In the paper the influence of sound generation in the tyre cavity is discussed in more detailed. For this the Chalmers Tyre/Road Interaction model is utilized. The simulations clearly show the contribution of tyre cavity resonances to rolling noise as function of surface type. The results indicate that additional damping in the cavity would not only be beneficial for the interior noise inside the vehicle but especially for rough road also for the exterior rolling noise due to tyre/road interaction.

Keywords: Tyre /road noise, speed exponent, cavity resonances, simulation

1 INTRODUCTION TO TYRE NOISE GENERATION

2 Introduction

Since many years it seems common understanding that there are mainly two mechanisms responsible for the generation of rolling noise; tyre vibrations and what is commonly referred to as air-pumping. While the understanding of the mechanisms behind tyre vibrations has progressed substantially during the recent years the mechanisms belonging to the category of air-pumping are rather speculative and is mainly based on the observation of a speed exponent close to “four” in measurements at higher frequencies (see e.g. [1]). There is no common agreement about the mechanisms behind “air-pumping”. the expression is rather used to describe a collection of acoustic sources which are all characterized by rapid displacement of air, in or near the contact patch. In order to be more precise the subsequent text refers to this group of monopole-like sources as air-flow related source mechanisms. The main phenomenological mechanisms suggested in literature are:

- In 1971 Hayden [2] suggested that, as the tread enters the leading edge of the road contact area, air is squeezed out as the tread is compressed and penetrates into the road surface. At the trailing edge, the tread is decompressed and lifts up from the road surface, with the result that air-flows back to fill the voids.
- Deffayet and Hamet [3] assumed that the opening and closing of cavities in the contact leads to sound generation. They measured the pressure in cylindrical cavities of different dimensions as a slick tyre rolled over the opening.
- Ronneberger [4] proposed that when the tread was deformed by roughness asperities intruding into the rubber there is air displaced due to the changing gap between rubber and road surface. He considered this flow as a monopole source and estimated the radiated sound.

None of these suggestions is able to satisfactorily explain the radiated sound pressure measured in field in a satisfying way. The lack of a models for air-flow related sources might be due to several reasons. First, an experimental investigation is very difficult since it is hard to directly observe the exact process in the contact between tyre and road during rolling without disturbing the process. Second, up to now there has been no

tyre/road interaction model able to describe the contact geometry in sufficient detail to simulate the air-flow related sources in the contact. In addition recent publications by [5] showed that a speed exponent of “four” even can be observed when only considering tyre vibrations as presented in section 3. With tyre vibrations as source for rolling noise one usually refers to the motion of the belt surface due to vibrations of the tyre structure. However besides the structural vibrations also the sound field inside the tyre cavity can lead to vibrations of the belt surface and therefore to sound radiation. Although this mechanism was brought forward from time to time as an important contributor (see e.g. [6]), it has never been really accepted as an important mechanism. This might be due to the fact that the air cavity only plays a role for the exterior radiated sound under certain circumstances as discussed in section 4 or that an experimental proof is not an easy one as damping the cavity always change the tyre structure as well. The simulations behind the results presented in section 3 and 4 are carried out by means of the Chalmers Tyre Road Interaction model CHATRIN. This is briefly described in following section.

3 BRIEF INTRODUCTION TO CHATRIN

CHATRIN has been developed at Chalmers University of Technology over many years. The main purpose of the model originally was to investigate tyre/road noise generation but has been extended to also predict rolling resistance. The complete model for the simulation containing a tyre model, a non-linear contact model and a radiation model. As it has a modular structure each of the three parts can be replaced by the most suitable tool for the application of interest. As standard a Wave Guide Finite Element model (WFEM) for the tyre structure is used. Results from this tyre model show excellent agreement both for radial point mobilities and transfer mobilities (see e.g. [7]). To reach such good agreement is a cumbersome procedure as it is less a question of modelling approach than on finding the correct material data as input into the model. After the vulcanisation process the material data have to be found experimentally and by comparison between model and measurements (see e.g. [8]).

The implementation of the contact model is in the time domain to be able to describe a fully transient non-linear contact. Its implementation is in line with the implementation used by Wullens and Kropp [9] and based on the PhD work by the author. Finally a half-space Boundary Element model developed by Brick [10] is used to calculate the radiation from a tyre placed over a rigid surface.

4 THE FAILURE OF SPEED EXPONENT AS INDICATOR FOR FLOW-RELATED SOURCES

The discussion on air-flow related mechanisms in literature is mainly based on speed exponent analysis. However, such analysis is not simple and often influenced by aerodynamic noise due to the movement of the vehicle. Winroth et al. [5] recently investigated the speed dependency of third-octave band tyre/road noise based on measurements as well as simulations. Similar approaches are found in recent publications (e.g. [11] and [12]). The main idea of the analysis in [5] is that the measured sound pressure can be composed of three terms

$$p^2(f, U) = A_2(f)U^2 + A_4(f)U^4 + A_6(f)U^6 \quad (1)$$

where A_2, A_4, A_6 is assumed to represent the contribution due to tyre vibrations, air-flow related mechanism and aerodynamic sources due to the flow around the vehicle respectively. This also includes the assumption that sound generation due to tyre vibrations is expected to be proportional to U^2 where U is the driving speed. The noise generation due to a time varying volume flow is expected to be proportional to U^4 and aerodynamic noise is proportional to U^6 . The study in [10] is based on measurement data from the so-called Sperenberg project [19]. In the project also wind tunnel measurements were carried out for the vehicles used in the measurement campaign. This allows for determining A_6 for each frequency band. With A_6 fixed, the optimal values of A_2 and A_4 were sought using a curve-fitting algorithm to model a sound pressure level with the logarithmic form of Equation 1 that best fits the measured or simulated tyre/road noise sound pressure level for each frequency

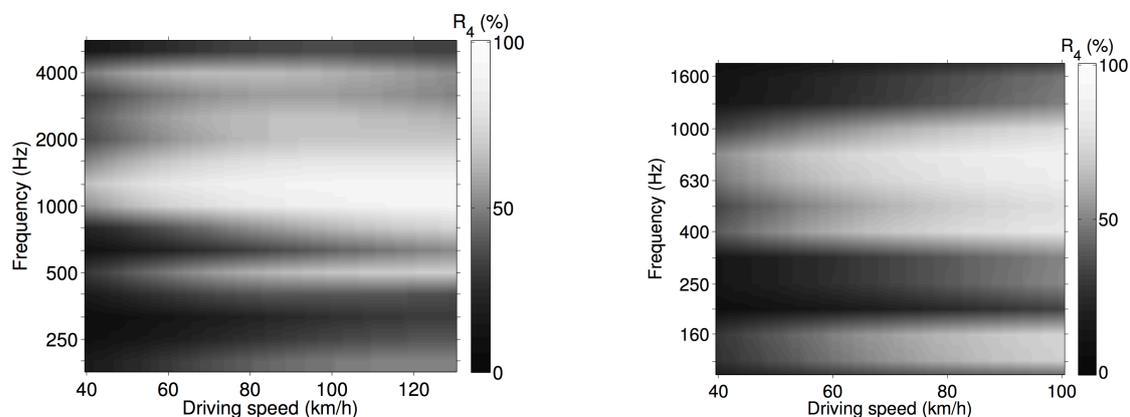


Figure 1. Contributions of the different source components to the total modelled source strength for a slick tyre rolling on a stone mastic asphalt surface; left: measurement from Sperenberg; right: simulation for a slick tyre on a rough surface similar to the surface in Sperenberg (from [13])

band. The results presented as ratios, R_m , representing the contribution of one source term A_m ($m = 2, 4, \text{ or } 6$) to the total source strength as shown in equation 2. R_m is illustrated in a colour plot where brightness is proportional to the percentage of a specific source as a function of third-octave band and evaluated speed U .

$$R_m = (A_m U^m) / (A_2(f)U^2 + A_4(f)U^4 + A_6(f)U^6) \quad (2)$$

From the results in [16] only two pictures are presented here to exemplify the problem with the interpretation of speed exponents to identify air-flow related mechanisms in measurements of tyre/road noise (see Figure 1).

These results as well as other results in [16] show important components of U^4 in measured tyre/road noise on rough road surfaces as expected around 1000 Hz. However they also show strong components of U^4 where it is expected that the noise is mainly generated by tyre vibrations. The U^4 component appears in the mid-frequency spectrum, around 400 to 500 Hz. Simulated tyre/road noise also shows an important contribution of U^4 , especially for rough road surfaces. Although the results are not identical, the tendencies are the same. The simulations show important components of U^4 around 1000 Hz, but also components around 400 to 500 Hz. The surprising part is that in the simulation, there is no flow-related mechanism included. The simulated tyre/road noise is only based on tyre vibrations. The conclusion is clear,

- noise from tyre vibrations can grow faster with speed than what has typically been assumed. The expected U^2 dependency is insufficient, a variety of speed exponents for tyre vibration-induced noise is found.
- it is also shown that tyre vibrations contribute to high-frequency tyre/road noise, giving reasons to discuss the classical division that “low-frequency noise is due to tyre vibrations and high-frequency noise is caused by air-pumping”.

5 THE INFLUENCE OF THE AIR CAVITY ON THE GENERATED EXTERIOR SOUND

5.1 Modelling the tyre cavity in the WFEM

To include the air-cavity into the WFEM has been described in detail by Nilsson [14]. The main tasks are to include the wave guide finite elements for the fluid and couple these to the structure. The exact implementation

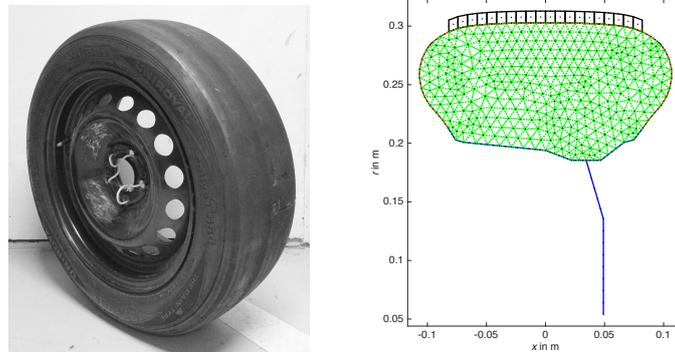


Figure 2. A 205/55 R16 tyre (left) and the corresponding WFEM (right)

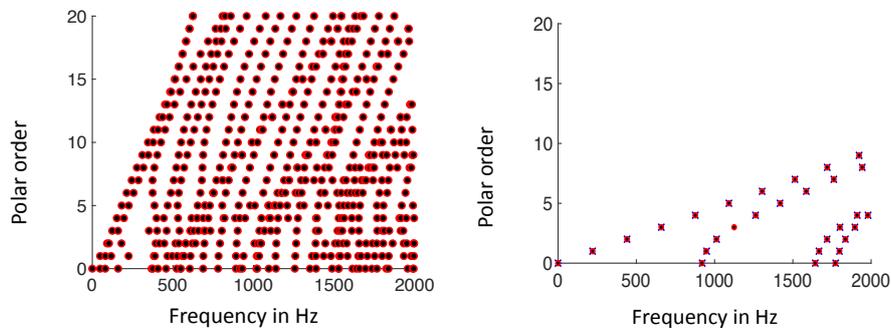


Figure 3. Dispersion diagram for all modes on the tyre (left) and for only the modes inside the air-cavity (right)

of these two steps in the WFEM used here is described by Hoever [15]. The model was implemented for an existing slick Continental tyre (see Figure 2, left side). The model consists of 46 deep shell elements for the sidewalls and belt. The tread is represented by 20 quadrilateral 9-node Lagrangian solid elements. Material data for this tyre are found in [7].

For the modified tyre i.e. with the air cavity and the rim, 28 shell elements are added for the rim, along with 707 triangular fluid elements and 69 shell-fluid coupling elements for the air cavity.

The rim is made of 4mm thick steel with a density of 7800 kg/m^3 , a Young's modulus of $210 \text{e}9 \text{ Pa}$, a Poisson's ratio of 0.31 and a loss factor of 0.005. For the air cavity a temperature of 20 degree Celsius and an inflation pressure of 200 kPa give wave speed of 344 m/s and a density of 3.56 kg/m^3 . Different loss factors are used in the air cavity as described in the further text.

Within the WFEM one extracts the eigenfrequencies of the lateral modes for each polar order (i.e. number of waves on the circumference). The results are shown in Figure 3 on the left side. An extensive discussion of those dispersion diagrams can be found in [7].

In order to easily identify the modes in the air cavity the pre-stress of the tyre structure as well as the density of the rim have been changed in a way that all structural modes have been moved up in frequency outside the frequency range of interest. The resulting dispersion diagram for the modes inside the air cavity is shown on the right hand side of Figure 3. Four branches can be identified which represent circumferential modes combined with four modal pattern in the cross section of the tyre cavity. The first branch does not have any variation of the sound pressure in the cross section. The second branch has a vertical nodal line, the third branch a

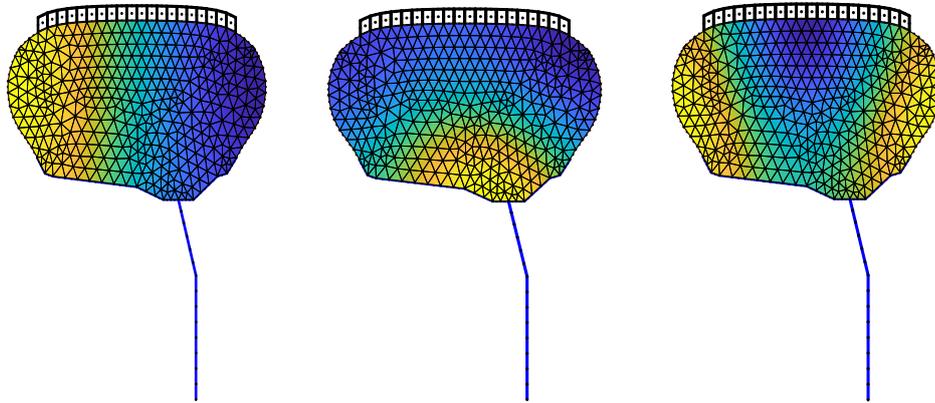


Figure 4. Shape of the cross sectional mode for branch 2 (left), branch 3 (middle), branch 3 (right)

horizontal nodal line and finally the fourth branch two vertical lines as shown in Figure 4.

All these modes would be very good radiators as their sound speed is equal or higher than the sound speed in air. The importance of these modes for the radiated exterior sound depends, however, on their amplitude when excited during rolling and the coupling between the interior sound field and the vibrations of the tyre structure.

5.2 Contribution of the cavity modes as function of road surfaces

The rolling simulations are carried out at a speed of 80 km/h and with an axle load of 3000 N per tyre. Two different surfaces are used. An ISO surface and a rather rough spit mastic asphalt. Both surfaces are roughness scans from surfaces used in the Sperenberg project [13]. Six parallel tracks are used in lateral direction a resolution of 0.5 mm in longitudinal direction. The sound pressure is calculated as mean sound pressure from 321 points on a half-sphere of radius 1 m around the centre of the contact between tyre and road. For each of the road surfaces the mean radiated sound pressure in third octave bands is calculated for two the tyre model including the air-cavity as well as for the tyre model without the air-cavity. Please note that both tyre models give almost identical structural responses. The mobilities are shown in Figure 5.

The mobility is measured and calculated in radial direction in the middle of the belt. For the measurement the tyre was freely suspended while for the calculations the tyre rim is blocked. This is the reason for the differences at very low frequencies between measurements and calculations as the freely suspended tyre does not show the very first resonance. The important differences between the two calculated mobilities are the small peaks in the mobility due to the resonances inside the tyre cavity. Higher order modes of the interior (e.g. from branch 2 or higher) are very hard to observe in the structural response of the tyre.

In Figure 6 the results of the simulations for the mean of the radiated sound pressure on the sphere are presented.

Two different loss factors for the damping of the tyre cavity are used, 0.003 indicated as “normal damping” in Figure 6 and 0.0003 indicated a “small damping”.

There is a clear influence by the air-cavity on the mean of the radiated sound pressure in the case of the very rough spit mastic asphalt surface while this influence is only marginal for the smooth ISO surface. Only for small loss factors in the cavity even for the case of the ISO surface the modes inside the air-cavity leads to an increased sound pressure. In general the influence of the cavity is only observed below 1000 Hz .

Closer investigations showed that the difference in results for the ISO surface and the spit mastic asphalt surface

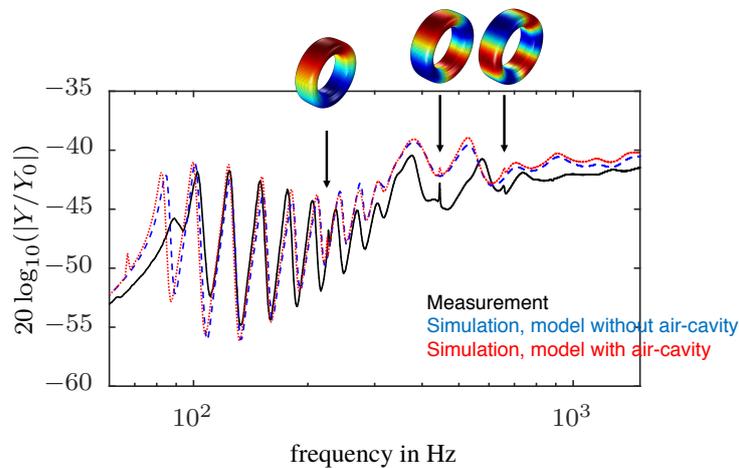


Figure 5. Simulated (with and without air-cavity) and measured radial driving point mobility for the 205/55 R16 tyre

could not be explained by a change in contact forces for the cases with and without taking the sound field inside the air-cavity into account. Both footprint and contact force spectra look more or less identical in both cases. The difference is found in the underlying physics of the excitation of the cavity. One can consider the tyre structure as a moving membrane radiating into the inside of the cavity. As the propagating waves on the tyre are very short in wavelength in comparison to the wavelength in air the question arises which is the effective volume flow fed by the “membrane” to the cavity. For this the velocity on the tyre structure was calculated for all elements and multiplied with the surface element size. The resulting total volume flow (i.e. sum over all elements) is presented in Figure 7. There is a clear difference in volume flow for both surfaces at frequencies below 1000 Hz. This might mean that the cavity is much stronger excited in the case of the spit mastic asphalt and consequently the contribution of the air-cavity to the total radiated sound field is stronger.

6 CONCLUSIONS

The paper showed that the contribution of air-floor related mechanisms (mostly named as air-pumping) are not as evident as often claimed in literature. To argue with the observed speed exponent in measurements is a weak or even erroneous argument as such speed exponents can also be observed when only simulating tyre vibrations. This does not mean that the observed phenomena such as closing cavities do not exist, but that maybe only in exceptional cases they might be of importance for the rolling noise generation. It also has shown that there is a need to extend the modelling of tyre vibrations by taking into account the sound field inside the air-cavity of tyres. The influence of the cavity modes on the generated rolling noise strongly depend on

- the damping inside the air-cavity
- the roughness of the road surface
- and the stiffness/mass of the tyre structure.

The influence is only observed at frequencies below about 1000 Hz. Although these findings increase the complexity of tyre/road noise simulations they also offer an additional degree of freedom for the reduction of tyre/road noise by adding more damping to the tyre cavity. Despite this one should however have in mind that

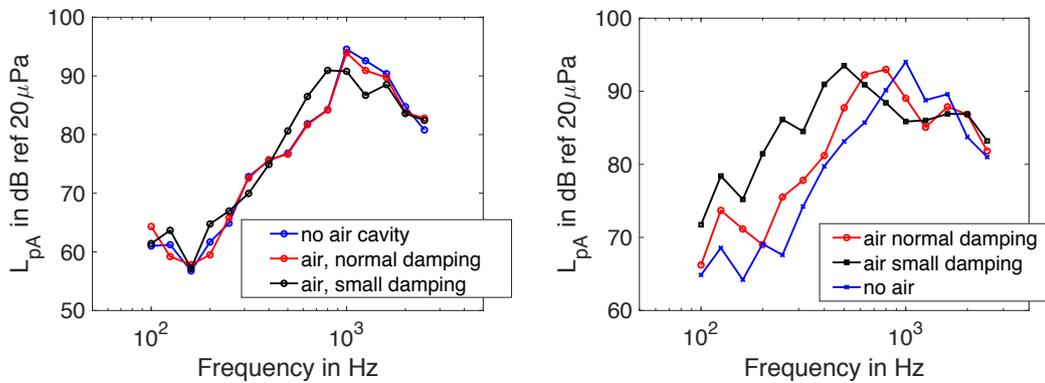


Figure 6. Third octave band spectrum of the calculated mean sound pressure level for an ISO surface (left) and spit mastic asphalt surface (right)

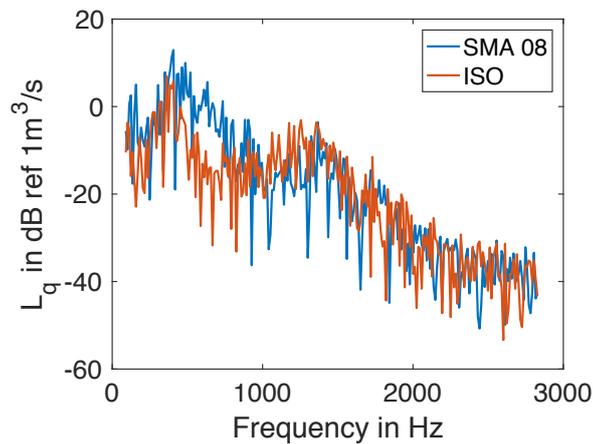


Figure 7. Calculated volume flow based on the vibration of the tyre structure

the simulation results for the case without taking into account the air-cavity represent the lower limit for an reduction by such measures.

REFERENCES

- [1] Sandberg, U. and Ejsmont, J. Tyre/road noise reference book. Informex, Kisa, Sweden, 2002
- [2] Hayden, R.E. Roadside Noise from the Interaction of a Rolling Tire with the Road Surface.
- [3] Hamet, J.F., Deffayet, C., and Pallas, M.A., Air pumping phenomena in road cavities. In proceedings of the International Tire/Road Noise Conference, Gothenburg, Sweden, August 8-10 1990
- [4] Ronneberger, D., Experimentelle und theoretische Untersuchungen spezieller Mechanismen der Rollgeräusche und Abstrahlung. In Mitteilungen des Instituts für Straßen-, Eisenbahn- und Felsbau an der ETH Zürich, 57 (1984), 79-116

- [5] Winroth, J., Kropp, W., Hoever, C., Beckenbauer, T., Männel, M. Investigating generation mechanisms of tyre/road noise by speed exponent analysis, *Applied Acoustics* 115, 101-108
- [6] Hoever, C., Kropp, W. A model for investigating the influence of road surface texture and tyre tread pattern on rolling resistance. (2015) *Journal of Sound and Vibration* 351, 161-176
- [7] Sabiniarz, P., Kropp, W. A waveguide finite element aided analysis of the wave field on a stationary tyre, not in contact with the ground. *Journal of Sound and Vibration* 329 (15), 4 (2010) pp. 3041-3064.
- [8] Hoever, C. The simulation of car and truck tyre vibrations, rolling resistance and rolling noise, PhD thesis (2014), Chalmers University of Technology.
- [9] Wullens, F., Kropp, W., A three-dimensional contact model for tyre/road interaction in rolling conditions. *Acta Acustica united with Acustica* 90(4), 4 (2004) 702-711.
- [10] Brick, H., Ochmann, M., Kropp, W. Point-source- scattering from tyre-like structures above an impedance plane. *NAG/DAGA 09, International Conference on Acoustics, Rotterdam*, 4 (2009).
- [11] G. Dubois, J. Cesbron, H. P. Yin, F. Anfosso-Lédée, and D. Duhamel. Statistical estimation of low frequency tyre/road noise from numerical contact forces. (2013) *Applied Acoustics*, 74(9), 1085-1093 (2013).
- [12] S. E. Paje, M. Bueno, U. Viñuela, and F. Terán. Toward the acoustical characterization of asphalt pavements: analysis of the tire/road sound from a porous surface. *Journal of the Acoustical Society of America* 125(1),5-7, 2009
- [13] T. Beckenbauer, G. Blokland, S. Huschek: Effect of pavement texture on tyre/pavement noise [Einfluss der Fahrbah-ntextur auf das Reifen-Fahrbahn-Geräusch]. Report FE-Nr. 03.293/1995/MRB, German Federal Ministry of Transport, August 2002.
- [14] Nilsson, C M. Waveguide finite elements applied on a car tyre. PhD thesis, KTH. Stockholm; 2004.
- [15] Hoever, C., Kropp, W. The Simulation of Tyre/Road Interaction and Exterior Rolling Noise for Road Surfaces With Transversal Discontinuities. *ProceedingsINTER-NOISE 2016, 45th International Congress and Exposition on Noise control Engineering, August 21–24 2016, Hamburg, Germany*