Tire/road noise – Characterization and potential further reductions of road traffic noise

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ABSTRACT

The first part of this paper compares results of two measurement techniques to characterize the tire/road noise radiation of a loaded rotating smooth (slick) tire on a coarse road surface. Sound pressure measurements at low spatial resolution with microphones placed on a half-hemisphere around the tire/road contact patch have been performed to calculate the radiated sound power. The second method makes use of a 3D sound intensity probe and yields a highly detailed spatial visualization of the noise radiation. The second part of this paper elaborates on a holistic approach to further reduce traffic noise. This approach includes the three major actors: tires, vehicles and roads. By considering the feasibility and potential of all individual actors, the highest societal benefit can be achieved.

Keywords: Tires and road-tire interactions, Road traffic noise

1. INTRODUCTION

Within the Environmental Noise Directive 2002/49/EC (1), environmental noise is defined as the “unwanted or harmful outdoor sound created by human activities, including noise emitted by means of transport, road traffic, rail traffic, air traffic, and from sites of industrial activity”. Tire/road noise is one of the sources of vehicle noise and thus contributes to the road traffic noise.

This paper reports on two measurement techniques to analyze the exterior noise radiation of a loaded rotating tire rolling on a coarse road surface. Both measurement techniques allow the spatial visualization of the noise radiation on a half-hemisphere around the tire as well as the computation of the overall sound power level. The first measurement technique is based on the ISO 3745 standard where sound pressure measurements are performed at low spatial resolution. The second measurement technique is based on sound intensity measurements at high spatial resolution. It uses a sound intensity scanning probe, the LMS Soundbrush. The results show that high spatial resolution method is able to provide detailed insight in the noise radiation that results from the interaction between the tire and the road surface.

The EU regulatory approach in the past has been concentrated on the automotive industry. As a result of strict regulatory requirements over the last two decades, the tire and vehicle industries in Europe have made significant technological progress to reduce their impact on road traffic noise, keeping at the same time balance with other essential performances such as road safety and fuel efficiency. In addition, low noise road surfaces became a valuable measure to reduce traffic noise (2). Therefore, there should be a comprehensive analysis of the three major actors – tires, vehicles and roads – in order to identify technical feasibility and potential for cost-effective noise abatement in the future. This paper illustrates the balance between tire/road noise and other performances, and invites for reflection on a holistic approach for noise optimization addressing tires, vehicles and infrastructure.

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2. SOUND POWER MEASUREMENTS

2.1 Low Spatial Resolution Method Based on Sound Pressure

The testing reported in this paper has been performed in a semi-anechoic room which is equipped with a rotating drum of radius 1.5 m. The drum is covered with a replica of a coarse road surface. The tire fixture provides the loading of the tire onto the drum. In order to avoid reflections, the tire fixture is covered by an absorbing foam. All reported testing is performed on a slick tire of size 205/55 R16 which is mounted on an alloy wheel. The tire operating conditions are: 60 km/h rolling speed, 4000 N tire load and 2.2 bar inflation pressure.

The position of the microphones is based on the ISO 3745 standard (3) which specifies 10 microphone positions on a hemisphere centered around the noise source. However, in the case of a slick tire and assuming symmetric road texture excitation, the assumption of symmetric noise radiation about the XZ-plane is valid. Therefore it is sufficient to measure on a half-hemisphere which contains 7 microphones. To ensure free-field conditions, the hemisphere radius is 1.5 m, which is more than 4 times the average distance of the source from the reflecting plane and not less than 1 m as prescribed by the ISO 3745 standard. Figure 1 shows a picture of the setup and the location of the microphones.

![Test setup for the low spatial resolution method based on sound pressure measurements on a hemisphere of radius r = 1.5 m](image)

Figure 1 – Test setup for the low spatial resolution method based on sound pressure measurements on a hemisphere of radius \( r = 1.5 \) m

Figure 2 shows sound pressure levels of the individual microphones which provide a spatial visualization of the noise radiation on a half-hemisphere around the tire. All noise spectra show a peak around 1000 Hz due to the coincidence of different effects such as road surface texture geometry spectrum, horn amplification and A-weighting. The horn amplification is especially apparent for Mic 1 and 6 in the vicinity of respectively leading and trailing edge. The main goal of this ISO 3745 standard is to determine the sound power level of a source. The sound power level is computed in two steps. In a first step (Equation 1) the individual sound pressure levels are weighted by the relative area of the half-hemisphere they are associated with. Note that the relative area associated with the individual sound pressure levels for the microphones in the ZX plane is half compared to the ones not in this plane.

\[
L_{psurf} = 10 \log_{10} \left[ \frac{1}{S} \sum_{i=1}^{N} S_i 10^{0.1 L_{pi}} \right]
\]  

(1)

with

- \( L_{psurf} \) = surface sound pressure level [dB, ref.: 20 μPa]
- \( L_{pi} \) = sound pressure level of microphone \( i \) [dB, ref.: 20 μPa]
- \( S_i \) = partial area of half-hemisphere associated with microphone \( i \)
- \( S \) = πr², total area of half-hemisphere
\( N \) = number of microphone positions.

In a second step (Equation 2) the sound power level is computed, assuming free-field conditions,

\[
L_w = L_{\text{psurf}} + 10 \log_{10} \left( \frac{S}{S_0} \right) + C
\]  

(2)

with

- \( L_w \) = sound power level [dB, ref.: 1 pW]
- \( S_0 \) = 1 m²
- \( C \) = correction term to be applied only if the room temperature and atmospheric pressure significantly differ from 20 °C and 10^5 Pa, respectively

Figure 3 shows the sound power level radiated through the half-hemisphere as calculated by equation 2.

Figure 2 – Sound pressure levels of the individual microphones

Figure 3 – Sound power levels radiated through the half-hemisphere resulting from both measurement methods.
2.2 High Spatial Resolution Method Based on Sound Intensity

The instrumentation consists of a sound intensity scanning probe, called LMS Soundbrush. The system consists of a handheld probe with a sound intensity sensor and a tracking position camera system, as shown in Figure 4. The combined system permits to visualize on-line the measured noise while moving the probe around the test object under investigation. The spatial resolution is rather high since a large number of measurements on different locations are made. The 3D sound intensity sensor, manufactured by G.R.A.S. Sound & Vibration, is a solid sphere with four phase-matched microphones in tetrahedron configuration (4). It allows the visualization of the noise radiation using sound intensity vectors. More detailed information on the sound intensity sensor can be found in reference (5). The 3D position of the probe is measured with an optical position tracking system. The probe comprises an illuminated sphere with 45 mm diameter which is continuously tracked by a camera. The 3D orientation of the probe is measured with an inertial system platform consisting of accelerometers and gyroscopes (6).

The probe has been used to scan a hemisphere with a radius of 1.5 m centered around the tire/road contact point. Based on the assumption of a symmetric noise radiation from the slick tire, only a half-hemisphere around the tire is scanned. Sound intensity is measured at each tracked position. The camera is moved in different locations in order to scan completely the half-hemisphere surface. Figure 4 shows an example of sound intensity vectors measured at a single camera location. The direction of the sound intensity vectors clearly shows the noise radiated from the rotating tire (figure 4). The color of the intensity arrows represents the overall sound intensity levels in the frequency range from 100 Hz to 4 kHz. Low sound intensity levels are depicted with dark blue, while the red arrows display areas of high intensity levels.

![Image](image.png)

Figure 4 – Left: LMS Soundbrush handheld probe with the sound intensity sensor and the camera used for the tracking position system. Right: Sound intensity vectors measured while scanning the half-hemisphere at one of the two camera locations.

Figures 5 show sound intensity levels over the half-hemisphere for some of the 1/3rd octave bands. The sound intensity fields are obtained by interpolating the measured sound intensity over the half-hemisphere. The high resolution visualization of the noise radiation on a half-hemisphere around the tire shows how the radiation pattern changes over the different 1/3rd octave bands. The noise radiation in 3 different regions around the tire (leading edge, side and trailing edge) will be further discussed.

The noise radiation at the leading edge is dominant compared to other regions from 500 to 1000 Hz. The sound intensity level in the leading edge region is on average 2-3 dB higher compared to the trailing edge region in this frequency range. The orientation of maximal radiation in the leading edge region changes from $\theta_L = 150$ deg at 500 Hz to $\theta_L = 180$ deg at 1250 Hz. The horn effect is apparent from 800 Hz to 1250 Hz. The sound intensity level in the leading edge region reaches a maximum at 1000 Hz.

The noise radiation in the side region is pronounced from 500 to 1000 Hz. The sound intensity level drops from 1250 Hz onward with 7-8 dB compared to leading and trailing edge region. The horn amplification effect is apparent in the side region.
Figure 5 – Sound intensity over the half-hemisphere for the 1/3rd octave bands 315 - 2500 Hz.
The noise radiation at the trailing edge is dominant compared to other regions from 1250 Hz onward. The sound intensity level at the trailing edge region becomes on average 3-4 dB higher compared to the leading edge region. The orientation of maximal radiation in the trailing edge region changes from $\theta_T = 45$ deg at 630 Hz to $\theta_T = 0$ deg at 1250 Hz. The horn amplification effect is apparent from 800 Hz to 1250 Hz. The sound intensity level in the leading edge region reaches a maximum at 1000 Hz.

Based on the sound intensity measurements, the partial sound power levels can be calculated by equation 3. $I_{nj}$ is the magnitude of the normal sound intensity component measured at position $j$ on the half-hemisphere surface and $S_j$ is the area of the segment of surface associated with position $j$.

$$P_j = I_{nj} \cdot S_j$$

The total sound power radiated through the half-hemisphere is computed by equation 4 as the sum of the partial sound power levels. $N$ represents the total number of segments over the measurement surface. Figure 3 shows the sound power level radiated through the half-hemisphere as calculated by equation 4.

$$P = \sum_{j=1}^{N} P_j$$

2.3 Comparison of Both Methods

Figure 3 shows a good correspondence between the 1/3rd octave sound power spectrum obtained from the sound pressure and sound intensity method. The sound power level for the individual 1/3rd octave bands differs on average by 0.5 dB(A). The overall sound power level differs by 0.2 dB(A). Consequently, the sound pressure measurements at low spatial resolution with strategically placed microphones provide a robust solution to compute the overall sound power level. However, the measurement technique represents a limitation in terms of a detailed spatial visualization of the noise radiation. The sound intensity scanning probe yields a detailed 3D representation of the noise radiation in a half-hemisphere around the tire and thus provides more insight and better understanding of the acoustical phenomena.

3. TIRE/ROAD NOISE GENERATION MECHANISMS

As the term tire/road noise indicates, both the tire and the road surface have an influence on the generation of noise. Figure 6 gives an overview of the main noise generating and amplification phenomena (7). The interaction between the rolling tire and the road surface results in tire vibrations and in the generation of pressure disturbances in the air surrounding the tire.

Figure 7 shows a schematic overview of the three processes involved in tire/road noise generation: tire/road interaction, sound radiation and sound propagation. The figure also highlights on which processes the tire, road and vehicle properties have an influence. The tire properties influence the tire/road interaction and the sound radiation. Acoustic absorption at the exterior of the vehicle can have an influence on the noise propagation. The road surface plays a key role since the road properties influence all three processes involved in the tire/road noise generation.

4. IMPORTANCE OF ROAD SURFACE CHARACTERISTICS

Most road surfaces are composed of aggregates (chippings) which are bound together with a binder. A cement concrete road surface is composed of stones and sand which are bound together with cement, whereas asphalt concrete road surfaces use a bitumen binder. The most relevant road surface characteristics impacting tire/road noise are (8): macrotexture, megatexture and porosity (acoustic absorption). Megatexture corresponds to the wavelength range of the texture between 0.5 m and 50 mm and is also referred to as unevenness. Macrotexture corresponds to the wavelength range of the texture between 50 mm and 0.5 mm which is related to the size of the aggregates. The term porosity refers to the air voids that exist between the aggregates in the pavement. Besides the drainage of water on the surface, the pores also provide drainage of the air that is entrapped between the tire and the road. This property significantly reduces some of the tire/road noise generating mechanisms listed in figure 6. In order for the porosity to be effective, the pores need to be interconnected. Typically, porous
surfaces have a 15-25 \% void volume. A higher porosity would reduce the durability of the road surface. Acoustic absorption is a property of the road surface that is closely related to porosity. The porosity gives the surface an acoustic absorption, which influences the reflection and propagation of the noise. Besides the tire/road noise, also the propagation of the vehicle power unit noise will be influenced by the acoustic absorption of the road surface.

Figure 6 – Tire/road noise generation and amplification mechanisms

In order to illustrate the influence of the road surface properties on the tire/road noise generation a laboratory noise test has been performed. The exterior noise of 6 tires of the same size, but with a very different tread pattern and construction has been measured on two road surface replicas. Figure 8 shows the footprint for each of the 6 tires. In addition, the noise of a slick tire (no tread pattern design) with low noise construction has been measured. The tires are rolling at 50 km/h on a drum which is fitted with a smooth and coarse road surface replica. Figure 8 shows the noise frequency spectra for the

Figure 7 – Schematic overview of the three processes involved in tire/road noise generation (based on (9))
7 tires measured on the two different road surfaces. The data shows that the road texture has a significant influence on the tire/road noise. In this example, the noise difference due to the road texture is much larger compared to the differences related to the tire, despite the very different tires used in the test. The results also show that the noise of the 7 tires is more similar on the coarse surface compared to the smooth surface. The smooth surface has a better ability to differentiate tires with a very different tread pattern. Among the different tires tested, the noise of the slick tire is the lowest. However, a slick tire cannot be used on public roads since this type of tire does not meet the minimum legal safety requirements. This example shows that the road surface properties have a significant potential to further reduce the tire/road noise.

Figure 8 – Noise frequency spectra of 7 different tires measured at 50 km/h on two road surface replicas.

<table>
<thead>
<tr>
<th>Tread compound</th>
<th>Noise at 50 km/h</th>
<th>Rolling Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. tread compound</td>
<td>Ref. level</td>
<td>Ref. level</td>
</tr>
<tr>
<td>High hysteresis tread compound</td>
<td>-0.5 dB(A)</td>
<td>25% worse</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tread grooving volume</th>
<th>Noise at 50 km/h</th>
<th>Rolling Resistance</th>
<th>Straight Aquaplaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. tread pattern</td>
<td>Ref. level</td>
<td>Ref. level</td>
<td>Ref. level</td>
</tr>
<tr>
<td>25% lower groove volume</td>
<td>-0.5 dB(A)</td>
<td>= Ref. level</td>
<td>15% worse</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tire belt</th>
<th>Noise at 50 km/h</th>
<th>Tire Weight</th>
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</thead>
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<tr>
<td>Standard belt</td>
<td>Ref. level</td>
<td>Ref. level</td>
</tr>
<tr>
<td>Heavy belt</td>
<td>-0.3 dB(A)</td>
<td>10% heavier</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>slick tire</th>
<th>Noise at 50 km/h</th>
<th>Rolling Resistance</th>
<th>Straight Aquaplaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>235/40R19</td>
<td>67 dB(A)</td>
<td>Ref. level</td>
<td>Ref. level</td>
</tr>
<tr>
<td>slick tire (low noise construction)</td>
<td>-1.5 dB(A)</td>
<td>10% worse</td>
<td>unacceptable level</td>
</tr>
</tbody>
</table>

Figure 9 – Effect of tire design changes on tire/road noise and other environmental & safety performances.

The noise is measured on an ISO10844 test track at 50 km/h.
5. FUTURE REDUCTION OF ROAD TRAFFIC NOISE

Both tire and road surface properties influence the tire/road generation. Figure 9 shows some examples of tire design changes which reduce the tire/road noise by influencing one or multiple noise generation mechanisms. The first example shows that a tread rubber compound with increased hysteresis reduces the noise radiation by 0.5 dB(A) at 50 km/h. However, this design change increases the rolling resistance of the tire by 25%. In the second example the volume of the grooves in the tread pattern is reduced by 25%. This results in a noise reduction of 0.5 dB(A) at 50 km/h and an unchanged rolling resistance. However, due to the lower groove volume the aquaplaning performance becomes 15% worse. In a third example the tire belt (typically, two steel reinforced layers with opposite angles which are placed between the plies and the tread) is replaced by a belt which has a higher stiffness and weight. This results in a 0.3 dB(A) noise reduction at 50 km/h and a 10% increase of the tire weight.

These examples illustrate that tire performances are not independent. The majority of tire design changes to reduce the noise have an adverse effect on other physical phenomena linked to safety & environmental performances. The example with the slick tire in figure 9 shows that the progress in tire technology has resulted in tire/road noise levels that are currently approaching the level of a slick tire. It is important to note that the noise level of a slick tire is close to the lowest achievable noise level for that size due to the absence of most tire/road noise generation mechanisms. Therefore, the remaining noise reduction potential of tires is limited and the resulting trade-offs will be pronounced.

Currently, vehicles, tires and road surfaces are separately optimized with respect to a wide range of performances, including noise, safety and environmental impact. This means that each of the individual actors has pursued noise reductions with the lowest trade-off on the other performances that are of importance to the individual actor. With the exception of road surfaces, the achievement of these noise reductions has been guaranteed through regulations on the maximum noise emission. However, a change in approach is needed to achieve further significant road traffic noise reductions. Therefore, a holistic approach for road traffic noise abatement is proposed which includes the three major actors (tires, vehicles and roads). Figure 10 compares the current and proposed future holistic approach for road traffic noise reduction. By considering the feasibility and potential of all individual actors, the highest societal benefit can be obtained. Balanced noise requirements on all major actors will guaranty a road traffic noise reduction with the lowest trade-off on the other important performances.

Figure 10 – Current sub-optimized and proposed future holistic approach for road traffic noise reduction

It is expected that rather small overall road traffic noise reduction will be obtained in the future if vehicles, tires and roads are further independently optimized for noise, safety and environmental
emissions. In a holistic approach where requirements are defined, based on the improvement potential and trade-offs from all actors, a much larger overall road traffic noise reduction can be obtained. Potentially also larger progress can be made in traffic safety and lowering the environmental impact compared to a non-holistic approach. The proposed holistic approach for road traffic noise reduction is aligned with the recently published CAETS vision on urban sound planning (10). The International Council of Academies of Engineering and Technological Sciences (CAETS) is an independent nonpolitical, non-governmental international organization which advises governments and international organizations on technical and policy issues related to its areas of expertise. CAETS recommends to study the total effect of combined measures in order to avoid sub-optimization and unnecessary costs for all parties involved. In order to reduce the negative impact of road traffic noise, CAETS proposes to use all available tools: reduction at source, near-road propagation abatements and urban planning. Related to the noise properties of road surfaces, CAETS proposes a control of the road surfaces.

6. CONCLUSIONS

In the first part of this paper, two measurement methods for tire/road noise have been analyzed and compared for a slick tire rolling on a coarse road surface. The method based on sound pressure measurements at low spatial resolution provides a robust solution to compute the overall sound power level. However, the measurement technique represents a limitation in terms of a detailed spatial visualization of the noise radiation. In addition to the overall sound power level, the method based on the sound intensity scanning probe provides a high resolution 3D representation of the noise radiation around tire. The detailed image of the noise radiation as a function of frequency provides a better understanding of the acoustical phenomena.

In the second part of this paper it is illustrated that the majority of tire design changes (tread pattern, mold shape, construction, and material) have an influence on the noise generation mechanisms and on other physical phenomena linked to safety & environmental impact. The progress in tire technology over the last decades has brought the current tire/road noise levels closer the noise level of a slick tire of the same size, which is the lowest achievable noise level due to the absence of most noise generation mechanisms. As a result, there is a smaller remaining noise reduction potential with more pronounced trade-offs associated to this noise reduction potential.

From a physical point of view, the road surface characteristics play a key role in all aspects of the tire/road noise generation. An example where different tires are tested on different road surfaces shows the important potential of reducing the tire/road noise by optimizing the road surface characteristics. Therefore, a holistic approach for road traffic noise abatement is proposed which includes the three major actors: tires, vehicles and roads. By considering the feasibility and potential of all individual actors, the highest societal benefit can be obtained by avoiding sub-optimization of vehicles, tires and road surfaces with respect to noise emission.

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