Separating the contributions from air-pumping and tyre vibrations by speed dependency analysis of tyre/road noise

Julia WINROTH¹; Wolfgang KROPP²; Carsten HOEVER³;
Thomas BECKENBAUER⁴; Manuel MÄNNEL⁵

¹,²,³ Division of Applied Acoustics, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
⁴ Müller-BBM Schweiz AG, CH-4123 Allschwil, Schweiz
⁵ Müller-BBM, D-82152 Planegg, Germany

ABSTRACT

Traditionally tyre/road noise has been divided into low-mid frequency noise caused by tyre vibrations and high frequency noise caused by various air flow related mechanisms, "air-pumping". It has also been assumed that these two processes grow in importance with different (vehicle) speed exponents. The purpose with this work is to investigate how to extract the different noise sources by a speed exponent analysis. Such analysis tool would e.g. indicate under which circumstances it is necessary to include air flow related sources in a tyre/road noise prediction model. The results show that it is possible to extract components of tyre/road noise that grow with the speed to the power of two and four. Expecting these contributions to be connected to tyre vibrations and air flow related source mechanisms respectively, it is found that the latter are present at surprisingly low frequencies. In addition, modelled results, only taking into account noise created by tyre vibrations, also show speed exponents larger than two. It is concluded that tyre vibrations can generate noise with a range of speed exponents making it futile to separate the two main tyre/road noise source mechanisms by a speed exponent analysis.

Keywords: Tyre/road noise, Air-pumping, Speed exponent, Tyre vibrations
I-INCE classification number: 11.7.1 Tires and road-tire interactions

1. INTRODUCTION

The most important generation mechanisms of tyre/road noise are believed to be tyre vibrations and various air flow related source mechanisms traditionally referred to as air-pumping. Tyre vibrations are excited due to time varying contact forces where the road roughness in the contact zone is the main factor. The understanding and modelling of contact forces in the radial direction, tyre vibrations and their sound radiation is state of the art today (1, 2). In the literature there are a number of specific air-pumping mechanisms which have been suggested and theoretically, experimentally or numerically tested e.g. (3–13). Yet, a general understanding of if, and and under which realistic conditions, air-pumping acts as an important contributor to tyre/road noise is still missing.

Correlation studies of e.g. road spectrum and tyre/road noise (14), or modelled contact forces and tyre/road noise (15) have been interpreted to indicate that a part of tyre/road noise can be attributed to air-pumping and that it is a high frequency phenomenon, approximately above 1000 Hz. One objection to this conclusion could be the absence of a discussion concerning the contact filter effect. This describes how the full amplitude of surface roughness with wavelengths that are much smaller than the contact length, can not be completely accessed by the tyre. In other words, the contact filter effect decouples the

¹ julia.winroth@chalmers.se
² wolfgang.kropp@chalmers.se
³ carsten.hoever@chalmers.se
⁴ thomas.beckenbauer@mbbm.com
⁵ manuel.maennel@mbbm.com
excitation of the tyre with the amplitude of road roughness of short wavelengths.

Kropp et al. (1) showed that mainly low order modes with eigenfrequencies in the low frequency range control tyre/road noise in a wide frequency range, all the way up to 2 kHz. They concluded that one possible explanation could be that the radiation efficiencies of these modes make them very important even if they are driven in a frequency range far from where they have their maximum amplitude. The complex tyre/road noise model used by Kropp has been further developed by Hoever who has shown that tyre/road noise can be accurately predicted, even above 1 kHz, by a model that only considers tyre vibrations - aerodynamical sources are not incorporated (2, 16).

A next critical step in the development of a complete simulation tool for tyre/road noise is to understand if, and under which circumstances, air-pumping is important to include in the model. The present study is an attempt to separate the different noise generation mechanisms in tyre/road noise by a speed exponent analysis. By this it is anticipated to better understand the significance of air-pumping in authentic tyre/road situations.

2. METHOD

2.1 Speed dependency of tyre/road noise

The acoustic pressure of tyre/road noise, $p^2$, is often found to be proportional to the vehicle speed, $U$, to the power of a speed exponent, $k$: $p^2 \propto U^k$. Commonly a speed exponent around 3-4 is found for tyre/road noise (17). In (18) more detailed numbers are given, noise from radial vibrations of the tyre carcass to are expected to have $k = 2.0-3.0$ and air-pumping noise is expected to have $k = 4.0-5.0$.

Hayden (3) was one of the first to introduce air-pumping as an important concept in tyre/road noise and his theory resulted in a $U^4$ relationship which holds in general for acoustic monopole sources. The next order, $U^6$, is expected for dipole sources, e.g. the noise created from periodic vortex shedding by the wind flow around an object. It is more complex to estimate the expected speed dependency of the sound radiation caused by vibrations of a structure like a tyre. In general, the radiated sound power is proportional to the rms-surface-velocity to the power of two, but one must also consider the radiation characteristics of the structure.

One way to assess the mechanisms which are involved in the creation of tyre/road noise is to study how the noise depends on the vehicle speed. A prerequisite is that the speed exponent for each noise source mechanism is known and not overlapping. In general a high speed exponent is in the literature taken as an indication of air-pumping and a low speed exponent is taken as an indication of tyre vibrations. This may be correct as a ‘rule of thumb’ but issues with the pitch of the tread pattern, or wind noise could make the conclusions less accurate.

2.2 The analysis approach

The idea of individual speed exponents for different noise generating mechanisms found in the literature (e.g. (18)) is in this study concretised into a suggested curve-fitting model. It is investigated if tyre/road noise mechanisms can be seen as separable source terms, with different speed dependencies, together forming the sound pressure level. To make the analysis feasible, the sources are as a first approximation assumed to be uncorrelated.

The acoustic pressure of the tyre/road noise as a function of vehicle velocity $U$ and third octave band center frequency $f_n$ ($n = 125, ..., 5000$ Hz) is modelled as:

$$p^2(f_n, U) = A_2(f_n, U) \cdot U^2 + A_4(f_n, U) \cdot U^4 + A_6(f_n, U) \cdot U^6$$

(1)

The first term in Equation (1) is connected with the contribution from tyre vibrations with $A_2$ being a coefficient determining the strength of this type of noise source. The second term with the coefficient $A_4$ represents the noise from monopole type of sources which all grow with $U^4$. The last term takes into account noise generated from wind flow around the vehicle, growing with $U^6$. The source coefficient $A_6$ is determined separately with data from wind tunnel measurements.

The next step is to assume that the source coefficients of the different types of noise sources do not depend on driving speed. This can be understood as a presumption that there is no pitch related phenomenon, or that there is an even or randomised distribution of pitch. This allows us to simplify our
The analysis is implemented in Matlab using its straightforward least-square curve fitting function \texttt{lsqcurvefit}. First the $A_m(f_n)$ coefficients are determined from wind tunnel measurements assuming a $U^6$ wind speed dependency of the noise. With $A_6(f_n)$ fix, the optimal values of $A_2(f_n)$ and $A_4(f_n)$ are sought in order to model a sound pressure level with the logarithmic form of equation (2) that best fits the measured tyre/road noise sound pressure level for each frequency band.

The analysis results are presented as ratios, $R_m$, of the contribution of one source term ($m = 2, 4, \text{or } 6$) to the total source strength, see Equation 3. $R_m$ is then illustrated in a colour plot where brightness is proportional to percentage of the specific source as a function of speed and frequency.

$$R_m(f_n, U) = \frac{A_m(f_n) \cdot U^m}{A_2(f_n) \cdot U^2 + A_4(f_n) \cdot U^4 + A_6(f_n) \cdot U^6}$$

\section*{2.3 About the measurement data}

The measurement data that is analysed in this work origins from the Sperenberg project (18) that was conducted at a former airfield in Sperenberg close to Berlin in Germany. It was a major measurement project where 3200 controlled coast-by sound pressure levels were recorded. 16 different car tyres were tested on 38 dense and rigid road pavements with several nominal driving speeds in the range from 50 km/h to 120 km/h. The speed exponent approach is in the present study applied on measured third octave band spectra produced at different vehicle speeds. They are based on a short piece of the coast-by noise taken when the A-weighted overall sound pressure level peaked. This introduces some uncertainty as it is not defined where the vehicle actually was positioned when the time signal was recorded. Further measurement data from the Sperenberg project as well as other test cites may provide more complete measurement data for future analysis.

Wind tunnel measurements were preformed as a part of the Sperenberg project with the two vehicles used in the coast-by measurements, a Volkswagen Polo and a Mercedes C-type. In the report (18) third octave band results for the latter vehicle are presented at three wind speeds, 80, 100 and 120 km/h. These results have here been extracted and a $U^6$-curve is fitted to them resulting in an estimate of the contribution from wind noise in the coast-by measurements.

Slick tyres on roads with broad roughness spectrum are mainly investigated in the present study to fulfill the requirement of an even pitch distribution for our analysis approach. An additional requirement on the measurement data is a sufficiently high signal to noise ratio of the tyre/road noise compared with the vehicle wind noise. In practice, this limits the studied Sperenberg cases to two rough road surfaces, a mastic asphalt surface with graywacke 2/5 (Figure 1a) and a stone mastic asphalt surface treated with a sharp edged 5/8 mm coating (Figure 1b).

\section*{2.4 The tyre/road noise simulation tool}

The tyre/road interaction model at Chalmers, presented in e.g. (1, 2, 16) is used to simulate tyre/road noise. Time domain Green’s functions are obtained from a waveguide finite element model of the tyre. These, together with the geometry of the tyre and the road, are used when solving the non-linear tyre/road contact problem to obtain the contact forces in each time-step. The contact calculation starts with a loading phase where the tyre is lowered onto the road until the right total contact force is reached. Then the tyre starts rolling with a fixed distance between the rim and the base line of the road, approximating the inertia of a complete vehicle. A steady state is usually reached after some revolutions when the effects of the loading have died out. The contact forces, here averaged over two revolutions, are then converted to the frequency domain with a Fourier transformation. This force spectrum is used as excitation to the waveguide finite element tyre model and the resulting vibrational field forms the input to the radiation module. This consists of a boundary element model where the tyre is placed above a hard, infinite plane and the sound pressure level is evaluated on a half sphere around the tyre.

The road texture data is based on multi-track laser measurements of real road surfaces. Linear contact springs are included in the interaction model to account for the small scale road roughness. Two surfaces
from the Kloosterzande test tracks (19) are investigated in this study, a smooth road build according to ISO-10844 and a rough road with surface dressing 5/8.

The upper limit of the frequency range in the tyre/road interaction model is proportional to the spatial resolution and the driving speed, very high frequency noise can not be calculated for low speeds without changing the resolution. It is presently not well understood how to change the spatial discretisation within a dataset in a controlled manner as the size of the elements affects the appropriate stiffness value of the contact springs. Hence the spatial resolution is kept constant in this study with 512 elements along the circumference of the tyre. Speeds between 40 and 100 km/h are utilised to create data sets similar to the measurements. Calculated sound pressure levels are shown up to the third octave band of 1600 Hz due to the frequency limitation for low speed.

3. RESULTS AND DISCUSSION

3.1 Analysis of measurement data

Coast-by measurements from two rough road surfaces are analysed: GA1 refers to a mastic asphalt surface (Gussasphalt) 0/11 with graywacke 2/5, see Figure 1a. A20 refers to a stone mastic asphalt 0/8 treated with a sharp edged 5/8 mm coating, see Figure 1b and Figure 1c for the roughness spectrum of A20. Two different slick tyres are used during the measurements: DB1 is the Continental 195/65-R15 91V model mounted on the Mercedes and VW1 is the 175/70-R13 82T model mounted on the Volkswagen.

Figure 1 – The two road surfaces used during the coast-by measurements: (a) GA1 mastic asphalt (Gussasphalt) 0/11 with graywacke 2/5. (b) A20 stone mastic asphalt 0/8 treated with a sharp edged 5/8 mm coating and (c) its roughness spectrum.
The case of the slick tyre DB1 on the rough mastic asphalt surface GA1 is shown in Figure 2 where the contribution of the different components to the total source strength can be seen. As expected, the $U^4$ term is important for the high frequencies, Figure 2b. Surprising though, is its share in the complex mid frequency range starting around 400-500 Hz where all three terms are active. Detailed results of the analysis for separate frequency bands are shown in Figure 3. The low frequencies are dominated by the $U^2$ term with a small contribution by the $U^6$ term for high speeds. As the frequency increases $U^4$ grows and becomes the most important component. In the highest frequency range, wind noise has again some influence on the data.

![Figure 2](image)

**Figure 2** – Contribution of the different source components to the total modelled source strength for the road GA1 with the slick tyre DB1.
Figure 3 – Examples of single third octave band analysis results for the road GA1 with the tyre DB1. Measurement data, the fitted function and its components.
Figure 4 shows the contribution of the $U^4$ term for two measurements on the rough stone mastic asphalt road surface A20 with the two different slick tyres DB1 and VW1. The $U^4$ component starts to become important around 400-500 Hz and dominates roughly from 800 Hz. The residual, which can not be seen in Figure 4, is for low speeds and low-mid frequencies dominated by the $U^2$ term. Wind noise is only noticeable in the very highest frequency bands.

Patterned tyres usually show clear pitch effects on smooth surfaces and such cases are not suitable for speed exponent analysis in third octave bands. However, the traces of pitch from the tread pattern seem to vanish on the rough surfaces as the contact is randomised by the road. As an example, the analysis result from the mastic asphalt road surface A20 with the patterned tyre "DB3", is shown in Figure 5b. DB3 is a Continental SportContact CH90 195/65-R15 90H mounted on the Mercedes, its pattern is pictured in Figure 5a. The contribution of the $U^4$ term seen in Figure 5b indicate similar trends as in the case with slick tyres on the same surface, see Figure 4. The main difference is that the $U^4$ term is focused around the 1000 Hz band. There is also a clearer transition from $U^2$ for low velocities to $U^4$ for higher velocities for the cases with patterned tyres in general.
3.2 Analysis of simulated data

Tyre/road noise simulations for a slick tyre on two road surfaces are presented in this study. Their roughness amplitude spectra, seen in Figure 6, clearly show their different character: the smooth road build according to ISO-10844 and the rough road with surface dressing 5/8.

The calculated tyre/road noise is assumed to consist of only two parts, the $U^2$ and the $U^4$ terms, as wind is not included in the model. Hence, the index $m$ in Equation 3 is reduced to $m = 2, 4$. Analysis results of the two cases are presented in Figure 7 which shows that there is a $U^4$ component in the calculated noise and that it is mainly found in the case of the rough road. Detailed third octave band results for the rough road are found in Figure 8. The tendency is the same when studying other calculated cases with the remarkable conclusion: Noise from tyre vibrations induced by rolling can have a variety of speed exponents, some of which extends into what classically has been interpreted as air-pumping.

Further investigations of modelled data is needed for a deeper understanding, e.g. how the speed exponent is dependent on the excited tyre modes and their radiation characteristics.

Figure 5 – Case of the patterned tyre DB3: (a) Tread pattern of DB3. (b) The $U^4$ contribution for the rough stone mastic asphalt road surface A20 with the patterned tyre DB3.

Figure 6 – Third octave band average of the road surface spectra over all tracks and positions on the test tracks for the two simulated cases: A rough road with surface dressing 5/8 and a smooth road build according to ISO-10844.
Figure 7 – Contribution of the $U^4$ component, $R_4$, for the simulated cases of a slick tyre on (a) rough surface (surface dressing 5/8) and (b) smooth surface (ISO-10844).

Figure 8 – Examples of single third octave band analysis results for the simulated case of a slick tyre on a rough road (surface dressing 5/8).
3.3 Discussion

Speed exponent analysis should strictly be applied on the total sound pressure level to include all types of possible pitch related effects. This study attempts to investigate the speed dependency of third octave band tyre/road noise and there are indications that it works sufficiently well. Compare e.g. Figure 9 where the speed exponent analysis is applied to the total level for the measurements of the slick tyre DB1 on the road surface A20, with the third octave band behaviour in Figure 4a. Both approaches show that the $U^4$ component is important and even dominates for higher speeds.

Finding a strong $U^4$ component in the noise from rough road surfaces is interesting as these are typically assumed to generate noise mainly by tyre vibrations. To complete the picture other surfaces should also be analysed, especially roads that are expected to generate significant air-pumping noise like sealed smooth surfaces and smooth surfaces with controlled cavities. However, a speed exponent analysis requires that the contribution from vehicle wind noise, the $U^6$ component, is known and/or negligible. The coast-by measurement data from Sperenberg indicates a domination and sometimes an overestimation of wind noise for quiet tyre/road combinations (18), i.e. slick tyres on smooth road surfaces. This makes a speed exponent analysis of these cases futile.

4. CONCLUSIONS

A speed exponent analysis is in this study used to extract noise generation mechanisms with different speed exponents from measured and simulated tyre/road noise. The initial suggestion was that noise from tyre vibrations and noise from air-pumping mechanisms grow with the speed to the power of two and four respectively.

An important component of $U^4$ is found in measured tyre/road noise on rough road surfaces where it is expected that the noise is mainly generated by tyre vibrations, not air-pumping. The $U^4$ component appears in the mid frequency spectrum, around 400-500 Hz and influences the noise up to very high frequencies. Simulated tyre/road noise also show an important contribution of $U^4$, especially for rough road surfaces. This occurs even if no aerodynamic sources are included, only tyre vibrations due to rolling generate noise in the model. This leads to the conclusion that noise from tyre vibrations can grow faster with speed than what has typically been assumed. The expected $U^2$ dependency is in this study proven to be 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 and the classical division that "low frequency noise is due to tyre vibrations and high frequency noise is caused by air-pumping", can be questioned.

The discouraging conclusion concerning air-pumping is that we still do not know its significance to tyre/road noise in authentic situations. The overlap with speed exponents from tyre vibrations makes it impossible to separate noise created by tyre vibrations from noise created by air-pumping with a speed exponent analysis.
REFERENCES