The contribution of air-pumping to tyre/road noise

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Introduction

Tyre/road noise generation is typically explained by two main mechanisms, tyre vibrations and what is commonly referred to as air-pumping. The understanding of the mechanisms behind tyre vibrations has progressed substantially during the recent years and today there are models that can calculate tyre road noise due to vibrations on a rolling tyre with convincing accuracy, see e.g. [1, 2].

The expression air-pumping refers to a collection of acoustic sources which are all characterised 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.*

Air-flow related source mechanisms are not very well understood and the models are to a large extent speculative. The following phenomenological mechanisms are suggested:

- In 1971 Hayden [3] 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 [4] 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 [5] 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. The lack of a model for air-flow related sources might be due to two reasons. Firstly, 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. Secondly, 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, it has been very unclear for which cases tyre vibrations is the dominant mechanism and for which cases air-flow related sources are more important. During the work by one of the authors with designing the SPERoN model based on the Sperenberg data it appeared that air-flow related noise played a more crucial role then expected from the literature (e.g. [6]). Traditionally tyre vibrations are considered as the main generation mechanism at low-mid frequencies while air-flow related sources dominate the high frequency range above 1000 Hz.

It is surprising that this question has not been investigated in more detail by for example analysing field measurement data. In order to close this gap, this paper evaluates the speed dependency in measurement data from the previous mentioned Sperenberg project. 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 of air is expected to be proportional to U^4. This difference in speed exponent is used to identify the contribution of each mechanism to the measured controlled pass-by levels. A variety of different road surfaces are investigated and measurement results are compared with results from a simulation model developed at Chalmers for tyre/road interaction.

The approach for the analysis of field data

In order to analyse the the speed dependence of measured Controlled Pass By (CPB) data, the acoustic pressure $p^2(f,U)$ is assumed to consist of two parts, one that origins from tyre vibrations and one part due to air-flow related mechanisms. Here f is frequency and U is driving speed. Each part is described by a source coefficient A multiplied with the driving speed raised to the power of the corresponding speed exponent:

$$p^2(f,U) = A_2(f,U) \cdot U^2 + A_4(f,U) \cdot U^4 \qquad (1)$$

If the underlying excitation can be assumed to depend only slightly on speed (i.e. the roughness spectrum is rather flat and only slick tyres are considered) the equation can be simplified to:

$$p^2(f,U) = A_2(f) \cdot U^2 + A_4(f) \cdot U^4 \qquad (2)$$

The strength of each source is then found by a least square fit method determining the unknown amplitudes A_2 and A_4. Figure 1 shows a typical result where air-flow related mechanisms and tyre vibrations together explain the measurement results. It is clear form the figure that both mechanisms are needed to explain the measured data, however air-flow related mechanisms are already important for rather low driving speed.

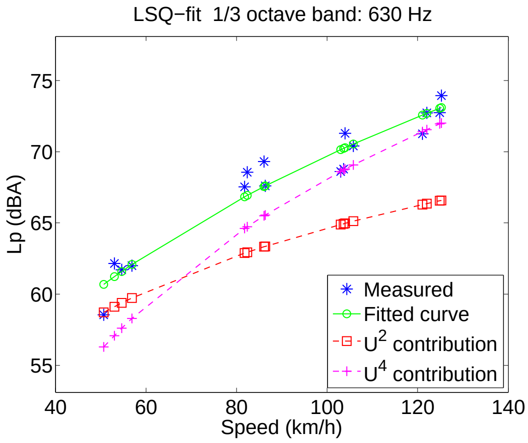

Figure 1: Both tyre vibrations and air-flow related sources contribute to the sound pressure level.

Analysis of measurements

At the end of the nineties a comprehensive measurement campaign was carried out where 3200 controlled pass-by (CPB) levels spectra 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 to 120 km/h [7]. Additionally, results of acoustic wind tunnel measurements yielded important information on the spectral behaviour and speed dependence of the residual air-flow noise from the used vehicles. The CPB measurements were carried out at a former air-field in Sperenberg close to Berlin, Germany. In the following some of these measurements are analysed in order to evaluate the contribution of air-flow related mechanisms to the radiated sound pressure level as function of frequency (third octave bands) and driving speed. Only a slick tyre is considered. Figure 2 shows the measured CPB levels as function of speed and frequency for a mastic asphalt surface. The different speed dependencies can already be seen as different slopes for different third octave bands. A more clear presentation of the speed dependency and in this way also of the importance of air-flow related mechanisms for the CPB levels is seen in Figure 3. It shows the contribution of air-flow related mechanisms in percentage of the total CPB level. Air-flow related mechanisms are as expected dominant at high frequencies above 1000 Hz. However they also have a very strong influence at the 400 Hz and 500 Hz third octave band, which is somewhat surprising.

Generally the trend is that the CPB levels at high speeds are only determined by air-flow related mechanisms. This was expected having in mind the strong speed dependency of this mechanism. Inspecting other road surfaces, similar results are observed. However when inspecting the results for very smooth surfaces, air-flow related mechanisms become the main contributor. Figure 4 shows the results for a stone mastic asphalt where the surface was sealed with synthetic resin. In this case only a very little part of the spectrum is determined by tyre vibrations. At very low frequencies and again at frequencies around 400 Hz as well as above 1000 Hz air-flow related mechanisms determine the CPB levels.

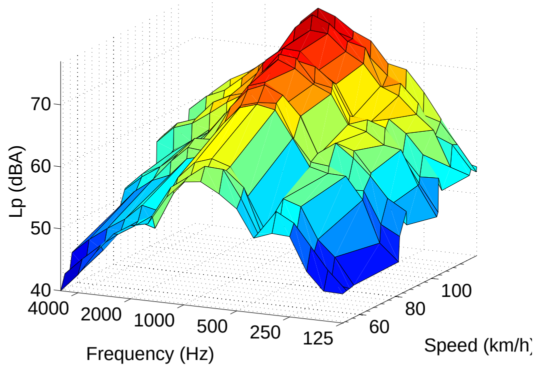

Figure 2: CPB level as function of frequency and driving speed for a slick tyre on a mastic asphalt.

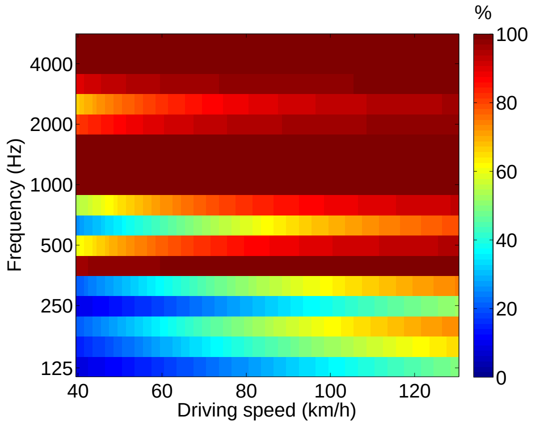

Figure 3: Influence of air-flow related sources for a slick tyre on mastic asphalt

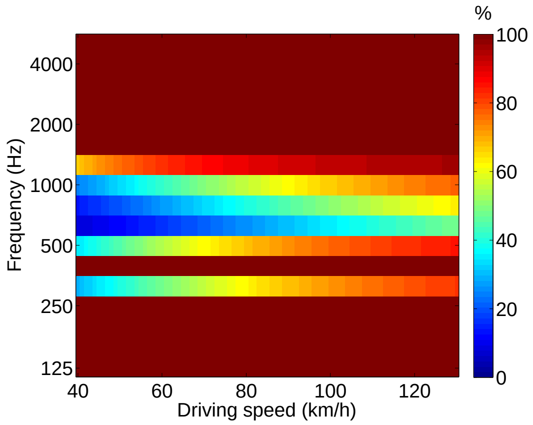

Figure 4: Influence of air-flow related sources for a slick tyre on sealed stone mastic asphalt

The influence of this mechanism is even further increased for a slick tyre rolling on a sand paper surface as shown in Figure 5. In this case the tyre vibrations seem not to be of any importance at all. The question arises if the dominance of air-flow related mechanisms is due to the fact that smooth surfaces are increasing the efficiency of these mechanisms or due to the absence of surfaces roughness relevant for the excitation of tyre vibrations.

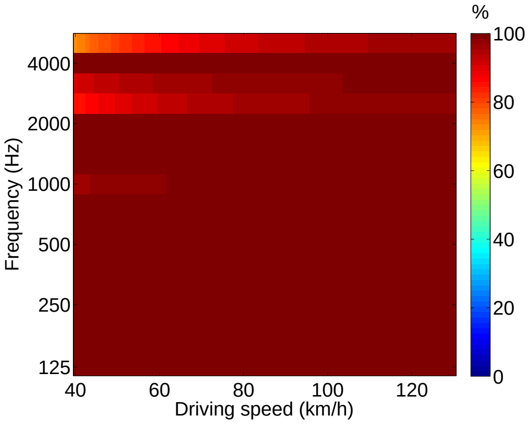

Figure 5: Influence of air-flow related sources for a slick tyre on a sand paper surface

Analysis of calculation results

During the last decades a tyre/road interaction model has been developed at Applied Acoustics, Chalmers University of Technology. It contains an advanced tyre model, a complete non-linear contact model an a radiation model also considering the influence of the road surface on the radiation. The model is applied to calculated sound radiation from rolling tyres, but also to predict rolling resistance as function of tyre and road properties [8]. The model is used to calculate the averaged sound pressure on a half-sphere around a tyre rolling on a road surface. The sphere has a radius of 1 m with its centre in the middle of the contact. The roughness of the road is included in the form of a geometry file based on multi-track laser measurement of the surface roughness. Two surfaces are investigated, an ISO surface and an asphalt surface with surface dressing 5/8. Calculations are carried out in the speed range between 40 and 100 km/h in 5 km/h steps. Due to the properties of the models the results for low driving speeds are limited to frequencies below about 2000 Hz. Therefore the following figures only show results up to the third octave band of 1600 Hz.

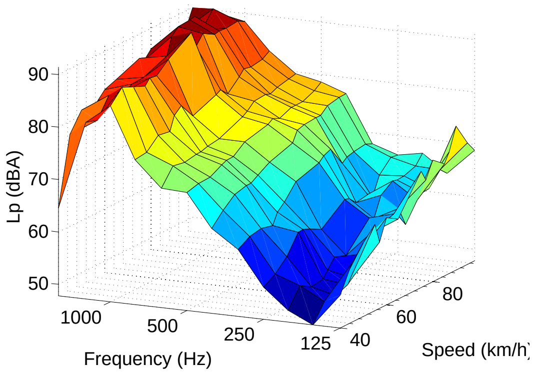

Figure 6: Calculated SPL for a slick tyre on a ISO surface replica

The calculated results for the ISO surface in Figure 6 show a similar structure as the CPB results for a mastic asphalt surface in Figure 2. The main sound pressure level is found around 1000 Hz and how different speed dependencies at different third octave bands can be seen. These speed dependencies are even more visible when inspecting Figure 7. Surprisingly enough, even the calculation results show the same principal behaviour with a strong contribution of air-flow related mechanisms at low frequencies, at around 400 Hz and finally at frequencies above 1000 Hz.

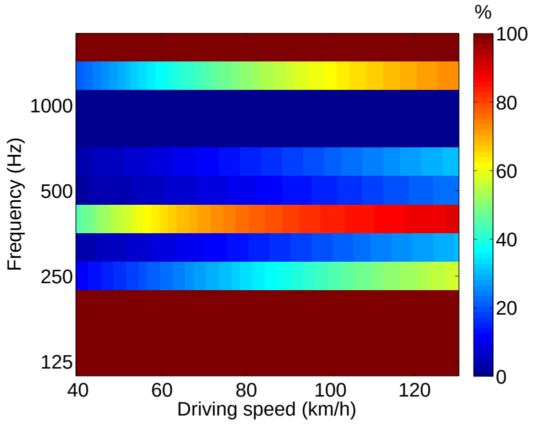

Figure 7: Influence of air-flow related sources for a slick tyre on a ISO surface replica

This is unforeseen in the aspect that the tyre/road interaction model does not contain any module especially capturing air-flow related mechanisms. This means that the observed monopole character in the calculation can only be due to the interaction between the vibrating tyre and the rigid surfaces. This interaction might lead to acceleration of air from the contact between tyre and road and in this way constituting a monopole sources leading to a strong U^4 dependency.

Similar results are obtained for the second surface as shown in Figure 8. Even here there is a dominant contribution of air-flow related mechanisms over the complete frequency range, especially at higher speeds.

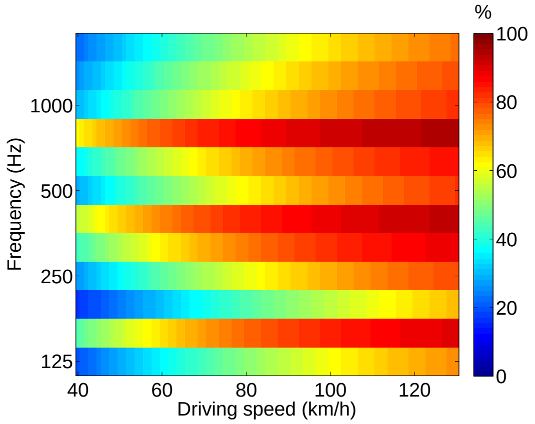

Figure 8: Influence of air-flow related sources for a slick tyre on a rough road with a surface dressing 5/8

Discussion and Conclusions

The difference in speed dependency of tyre vibrations and air-flow related mechanisms is utilised to investigate the influence of tyre vibrations and air-flow related mechanisms on tyre/road noise. The results show a very strong influence of air-flow related mechanisms not only at frequencies above 1000 Hz but also at very low frequencies an especially at around 400 Hz. This observation was confirmed by calculation results with the tyre/road interaction model at Applied Acoustics Chalmers University of Technology. The simulation results show very similar contributions of air-flow related mechanisms over the whole frequency range, despite the fact that the model does not include any special approach to capture air-flow related mechanisms. This leads to the conclusion that the air-flow related mechanisms observed both in measurement and calculation have to be included in the interaction between the vibrating tyre and the rigid road surface, leading to air being accelerated from the contact area. This acceleration of air obviously leads to source terms with monopole characteristics.

It is not clear if the dominance of air-flow related mechanisms especially for smooth road surfaces is due to the fact that smooth surfaces are increasing the efficiency of the underlying mechanisms or just reduce tyre vibration so strongly that air-flow related mechanisms only are remaining.

Finally the question arise if the results will change substantially when considering profiled tyres instead of a slick tyre. The excitation by the profile is expected to lead to stronger tyre vibrations. Figure 9 shows an analysis of measurement results for a profiled tyre running on mastic asphalt.

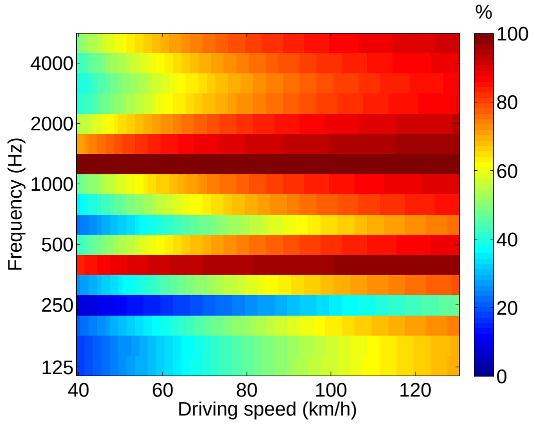

Figure 9: Influence of air-flow related sources to the total level for a profiled tyre on mastic asphalt

Even in this case the observation made for the slick tyre holds. It is also interesting that the behaviour in the 400 Hz third octave band does not change. The main influence of the profile seems to be at frequencies above 1000 Hz where, for low driving speeds, tyre vibrations is a stronger contributor than for slick tyres.

Finally it can be concluded that the influence of air-flow related mechanisms is much stronger than known form literature and that the influence is strongly depending on a variety of parameters such as tyre profile, surface texture, frequency and driving speed. One could also argue that the observed air-flow related mechanism is due to tyre vibrations, since the vibration of tyres in relation to the rigid surface is leading to the acceleration of air. This mechanism is certainly especially efficient if the tyre is moving in phase and with similar amplitude over the whole tread cross section. This might also explain the strong air-flow related contribution around 400 Hz where tyre radiation have been found to be mainly determined by the so-called breathing mode of the tyre [2].

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