TYRE/ROAD NOISE GENERATION – MODELLING AND UNDERSTANDING

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1 INTRODUCTION

Tyre/road noise generation is a fascinating research area from an intellectual point of view. It includes fields such as structural acoustics, contact mechanics, fluid mechanics, radiation of air-borne sound, and material science. That the subject is of high relevance for a successful reduction of road traffic noise, increases its attraction further. Although tyre/road noise has been subject to research during the last 30 years, the complete understanding of the noise generation mechanisms is still not accomplished. Different mechanisms are dominating at different frequencies depending on driving speed, tyre parameters and road surface characteristics. In order to predict the contributions of different mechanisms, models are needed that take into account the properties of tyres, the contact between tyre and road, and the radiation from tyres including aerodynamic sources such as air-pumping. To design such models also demands a sound understanding of the physics behind the tyre/road interaction. In this way the activity of modelling is an important step towards a better understanding and description of the tyre/road noise generation.
Today’s models are certainly far from being complete, but they focus on the most important effects for typical situations of interest. One should have in mind this fact when applying such models in order to draw general conclusions on tyre/road noise generation. While today much emphasis is put on numerical methods for simulating tyre/road noise generation, during the seventies and eighties research effort considered mainly the understanding of phenomena behind the generation processes. It is fascinating to read the proceedings of the first international workshop on tyre/road noise generation in Stockholm[1]. One has to admit that many of these questions discussed in the proceedings are still relevant and without definitive answer. Since then a series of research programmes has taken place and different attempts have been made to develop prediction models for tyre/road noise. These prediction methods are based on different philosophies and different approaches. The methods cover the wide range from Finite Element approaches, modelling details as exact as possible, to statistical approaches, quantifying the influence of main parameters influencing tyre/road noise. Kuijpers and Van Blokland[2] at the Internoise 2001 presented a comprehensive overview over these models. The following text will therefore focus more on the coupling between understanding and modelling of tyre road noise generation.

2 SUBJECT OF MODELLING – WHAT DO WE KNOW?

There are excellent overviews of the state of the art concerning generation mechanisms in the literature. Heckl’s overview at the workshop in Stockholm[1] can be considered as one of the first attempts to sort out the different mechanisms and validate their relevance. Recently a reference book on this topic has been published by Sandberg and Ejsmont[37]. The book can be considered as a quite complete collection of both experimental and theoretical results from the beginning of tyre/road noise research until recently. However, even this collection leaves a number of open questions.
Basically two different types of mechanisms can be distinguished, mechanisms exciting the tyre structure to vibrations, leading to radiation of sound, and aerodynamic effects.
Sound radiation is mainly due to radial vibrations of the tyre structure as well as the vibrations of the sidewalls. The excitation of vibrations demands time varying forces acting between the tyre and the road. The changes of contact forces over time can be due to different effects: the non-uniformity of the tyre, inhomogeneities (e.g. the tyre non-uniformity) and defects of the tyre structure, tread

pattern geometry, road texture, processes in the contact such as stick slip and stick snap. Firstly, the tangential and radial forces lead to friction mechanisms which in turn lead to stick-slip when the tread blocks are in contact with the road. Secondly, when the tread blocks are on the way to loose contact with the road, some adhesive forces will tend to keep them in contact with the road. At the same time, stick-snap will appear. Figure 1 illustrates the different generation mechanisms of tyre vibrations.

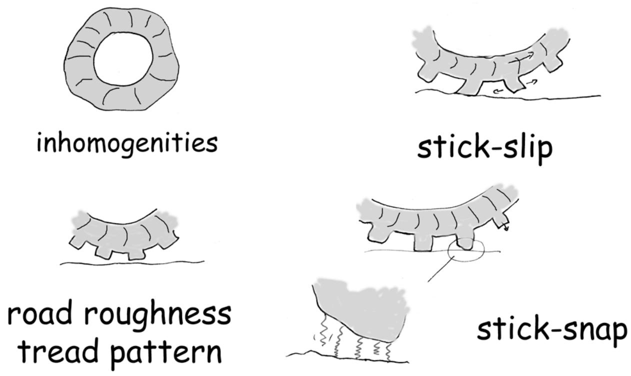

Figure 1: Generation mechanisms related to tyre vibrations.

Which of these mechanisms are dominating at which frequencies is not always easy to predict. The wide range and complexity of different tyre/road combinations make a general answer difficult and might even lead to confusion. However, one can conclude that there is a general agreement on the mechanisms behind the generation of sound due to the vibration of the tyre structure.

The situation becomes more confusing considering aerodynamic sources. There is a general agreement that while the tyre is rolling, some air is pumped out at the leading edge and sucked in at the trailing edge. As long as the amount of the air flow is time invariant there will be no sound generation having in mind that it is the rate of change in the airflow which is responsible for the sound generation. Heckl[1] made a simple estimation of the amplitudes required for these mechanisms to explain typical measured sound pressure levels for rolling tyres on a rough road surface. He concluded that, at least for low frequencies, this mechanism could hardly be of importance. Later it was shown by for instance Eperspächer[3], who correlated the radiated sound pressure with the measured vibration of the tyre structure, that tyre vibrations are important below about 1000 Hz while aerodynamic sources might take over at frequencies above 1000 Hz. In the German project “Sperenberg”, Beckenbauer[4] made a very thorough study of pass-by noise for different road and tyre combinations. For a number of these combinations – but not for all – the speed exponent (i.e. the change of the sound pressure amplitude as function of driving speed) changes from “3” indicating mechanical sources to “4-5” indicating aerodynamic sources when passing 1000 Hz. It could be interpreted as air-pumping. However, how the air pumping mechanisms work in detail is explained in different ways and, as often when disagreement occurs, the explanations might be correct for certain cases but they might not give a general answer.

In 1971 Hayden[5] presented the first semi-quantitative model of tyre noise excitation, and this was based on air pumping. Hayden proposed that, as the tread enters the leading edge of the road contact area, air is squeezed out as the tread is compressed and as it 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 rushes back to fill the voids.

Some investigations of a smooth tyre rolling over a cavity in the road were carried out at INRETS (Deffayet[6] in 1989 and Hamet et al.[7] in 1990). They measured the pressure in cylindrical cavities of different dimensions as a slick tyre rolled over the opening. The internal pressure increased very rapidly at the approach of the tyre and remained at a constant high level as the tyre obtruded the cavity. External measurements at the entrance of the contact patch showed no acoustical signal during this phase. When the cavity opens, the pressure signal oscillates and decays more or less rapidly depending on the cavity dimensions.

A third mechanism was described by Ronneberger[8]. He derived a model for the local deformation of the tread by roughness intruding into the rubber and calculated the volume flow due to the displacement of the rubber surface. From this he derived a model for the radiated sound pressure. Results showed very good agreement with measurements, at least for the cases considered in his studies. Figure 2 summarises the both main ideas.

Figure 2: Aerodynamic sources in the contact area between tyre and road.

In a personal communication Ronneberger later pointed out that he also found cases where the model failed completely and that this was the reason why he did not follow this line in his later work. From today's point of view, this might not have been due to the models shortcomings but due to the complexity of the tyre/road noise generation. The multitude of generation mechanisms makes the picture of tyre/road noise generation diffuse and the decision for a modelling strategy rather difficult. The problem becomes even larger due to the complexity of the radiation conditions for both vibrations and aerodynamic sources.
The so-called horn effect as explained by Ronnneberger[9] leads to an amplification of the radiation depending on geometry, source location, and acoustic properties of the road surfaces. Further resonance effects in the contact areas (e.g. resonances inside partly or fully open grooves) are identified as additional sources of noise generation in some publications. This is rather confusing and the effects are better considered as additional amplification effects for the radiation from the vibrating/moving tyre structure. In this context one might also refer to Graf's PhD thesis[38], where both the horn effect and resonances in the grooves were investigated.

2.1 Modelling Tyre/Road Noise Generation

There are certainly different ways to design prediction models for tyre/road noise generation. During the years a number of models have been developed with the intention to deal with the complete problem or particular details of tyre/road noise generation. The authors hope the reader will forgive them not to take up all these models but rather to focus on what they know best, which is the design of their acoustic rolling model. The strategy used by the authors is based on work published by McIntyre et al.[39] in the area of musical acoustics. They were interested in the interaction between violin bow and string. This interaction is of non-linear nature since tangential forces will excite the string to vibrations and at the same time the vibrations (i.e. velocity) of the string will determine the friction forces.
Their main idea was to describe the string as a linear system by its impulse response function (i.e. the velocity response to a force pulse with unit amplitude). This leads as shown in the further text to a very simple equation system, which can be solved for each time step. Following this idea one can win two important features for the rolling model, an elegant way to solve the contact problem and the use of pre-calculated impulse response functions, which reduces the numerical effort substantially when comparing with for instance an implicit formulation in Finite Elements. The approach also allows for treating the models for the tyre, the contact and the radiation separately. In this way one can always use the model with the most appropriate features with respect to complexity, numerical efficiency, accuracy, etc.. Such a division in sub-problems is also very meaningful in order to create both intellectually and computationally feasible tasks. In the following the modelling of the tyre structure, the contact and the radiation are described.

2.2 A Model For The Tyre Structure

Although a very first model for a tyre was presented by Böhm[10] already in 1966, there is still work going on to develop improved models and to increase understanding. Analytical models were presented by e.g. Pinnington[11] and Larsson[12], numerical models based on FE codes are used in tyre industry. Bolton[13] presented a beautiful analysis of the wave field around the tyre. This analysis gives clear hints for the modelling of tyres and the numerical effort, which should be invested to describe tyre vibrations. During the years a number of findings were published based on experiments or on the analysis of theoretical models (see for instance Kropp[14]). Figure 3 shows as an example a radial driving point mobility measured on a slick tyre. Typical observations are that:

- At low frequencies the first circumferential modes are visible. At these frequencies the tyre response is mainly determined by the tension due to the inflation pressure. At higher frequencies the flexural stiffness of the tyre structure is dominating.
- Around 400 Hz the modes in the width direction of the tyre start to propagate. While at frequencies below 400 Hz the radial mobility has beam character, at higher frequencies the tyre behaves more like a plate. This is also nicely shown by Bolton's results.
- Removing the rim will only lead to changes at frequencies below 300 Hz.
- A variation of the size of the excitation area will lead to different results at high frequencies. The rubber is locally reacting as a spring. This so-called local deformation is for instance included in Larsson's two layer model.
- At around 230 Hz the first resonance in the interior tyre cavity can be observed. This first resonance is together with the very first circumferential modes especially important for the generation of vibrations at the hub and consequently for the interior noise.

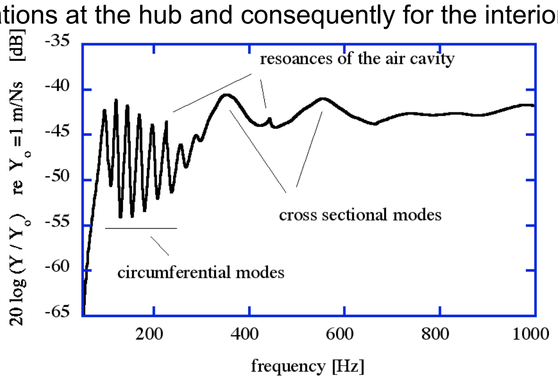

Figure 3: Radial driving point mobility Y for a smooth tyre excited in the middle of the tread

There are certainly more details to add which, however, might be beyond the scope of this paper. However, it is at least remarkable that very little variance is observed when carrying out driving point mobility measurements on a group of tyres of identical type. Today we are capable to model the tyre in detail with fairly good success. The main difficulties are due to the complexity of the tyre geometry and material data. Either the tyre has to be modelled on a compound level or equivalent material data such as flexural stiffness tension, etc have to be identified by measurements. Additionally it is not very clear how important the changes of material properties are when loading the tyre or when the tyre is rolling. In this case one could conclude that the accuracy of modelling today is not limited by the models but by the lack of accurate input data. The models for tyres can be distinguished by the frequency range, for which they are designed.
One of the first low frequency models was the circular ring model developed by Böhm[10]. The tyre belt is modelled as a ring on an elastic foundation. The foundation represents the sidewalls and the enclosed air in the tyre cavity. The ring is exposed to a tension force due to the inflation pressure. The model takes radial, tangential and lateral motions into account. A series of publication followed this work improving Böhm's model (see for instance[15-21]). These models have in common that they approximate the tyre structure by simple shells and membranes, not taking into account the exact internal structure or the elastic behaviour of the tread. In the most recent decades, computer development has made it possible to make detailed analysis of such complex structures as tyres by the use of the Finite Element Method (FEM). However, the method has a drawback: it is difficult to use at high frequencies, not only because of the high computer capacity required for the analysis

but also because of the need for good material data, which is very crucial for the modelling. A number of examples in which FEM has been applied to tyres can be found in the literature[22-25].
Medium and high frequency models typically focus on frequencies above the ring frequency (this frequency is between 200 to 400 Hz), where the curvature of the tyre can be disregarded. The radial and tangential motions can be considered uncoupled. The measured radial driving point mobility approaches that of an infinite plate at high frequencies. Above approximately 400 Hz, waves also propagate in the lateral direction of the tyre. Waves travelling along the tyre are effectively damped out due to high dissipation in the rubber material. To model the vibrational properties the orthotropic plate model is proposed[14], where the tyre belt is modelled as a finite plate with different properties in the circumferential and lateral directions. The plate is supported by an elastic bedding, representing the side walls and the enclosed air cavity, and is subjected to an external tension force that results from the internal pressure. More advanced models but following the same main idea can be found in the literature[26]. Finnveden[27] presented a spectral finite element method, which has been applied to calculate the dynamic response tyres of e.g. by Nilsson[28]. This model probably has the highest potential since it is correct with respect to geometry but still feasible in the whole frequency range of interest. However, it needs input data from the design board of tyre manufacturers.
Most of the models described above are based on theories that do not take into account the local deformation of the tread. Larsson thus developed a high frequency model[12] that is based on the basic elastic field equation. This model considers two elastic layers under a tension caused by the inflation pressure. It allows considerations to be taken to the vibrations, both radial and tangential, of the outermost tread layer, which have a significant influence on the contact between the tyre and the road and thus on the generation of high frequency noise. Various high frequency effects such as stick-slip motion of the tread and tread blocks, air pumping and air resonant radiation are determined by the geometry and the motion of the surface of the outermost tread layer, together with the properties of the road. The local deformation may of course be included in a FE model by adding several layers of solid elements to model the tread, but it seems that there is still some hesitation about doing this because of the computational effort necessary. Larsson's model reproduces this for the noise generation important effect of the local deformation in a satisfying way, as shown in the Figure 4.

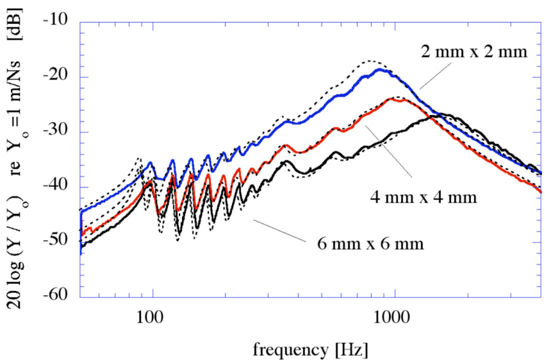

Figure 4: Radial point mobility for four different excitation areas: calculations with excitation areas of 2 mm x 2 mm, 4 mm x 4 mm ,and 6 mm x 6 mm (dashed lines) and measurements made with excitation areas of radius of 2.3 mm, radius 4.5 mm, and radius 6.9 mm (solid lines).

For the purpose of calculating the contact forces between tyre and road surfaces an appropriate model can be chosen out of the multitude of models. Which model will be chosen depends on the complexity of the contact model and the frequency range of interest. For tyre/road noise a frequency range up to 3 kHz is often required, while tangential motion in the tyre structure often seems to be of minor importance.

2.3 Contact Models

The problem to describe the contact between tyre and road may be studied at different scales. The fundamental elements of surface physics are the bonds between atoms or molecules that may be strong (ionic, covalent or metallic) or weak (hydrogen or van der Waals) and are all due to electromagnetic force. In a solid or a liquid these are the bonds that must be broken in order to create a new surface. Such models haven not been used in the simulation of tyre/road noise generation.

At a larger scale the interaction of elastic bodies can be studied by applying models like contact stiffness or friction coefficients having their origin in the physics behind the interaction of molecules. It is this scale for which today's contact models are mainly formulated.

As a first starting point one could think about the tyre as a structure where a Winkler bedding is added (i.e. a model of isolated springs). These springs represent the local stiffness of the rubber layer of the tyre. The contact forces at any point in the contact are consequently given by the stiffness of the bedding and its compression. The compression of the spring $\Delta y_e(\varphi_e,t)$, at the angle φ_e is a function of the centre of the rim $y_0(t)$, the curvature $k_2(\varphi_e)$ of the tyre, the vibration $\xi_e(\varphi_e,t)$ of the tyre belt and the roughness $k_{10}(\varphi_e,t)$ of the road.

$$\Delta y_e(\varphi_e,t) = y_0(t) + k_{10}(\varphi_e,t) + \xi_e(\varphi_e,t) - k_2(\varphi_e) \qquad (1)$$

The contact force is then

$$F_e(\varphi_e,t) = s\Delta y_e(\varphi_e,t)H\left[-\Delta y_e(\varphi_e,t)\right] \qquad (2)$$

where H is the step function. Since the motion of the tyre is a function of the forces, a non-linear equation system has to be solved for each time step in order to obtain the contact forces.

$$\xi_e(\varphi_e,t) = \sum_{m=1}^{M} F_m(\varphi_m,t) * g_{m,e}(t) \qquad (3)$$

$g_{m,e}(t)$ is the impulse response function of the tyre structure at position e due to an impulse at position m. The implementation in the time domain allows for considering non-linear stiffness for the contact or relaxation for the rubber material.

A more detailed description of this can be found for instance in the literature[29]. In such a model only contact forces normal to the surface are considered. A model taking into account tangential forces was presented by Larsson[30] but it has not yet been implemented. Although the original model was only two-dimensional there is no limitation in this, it can easily be extended to three dimensions and also to the case where the springs are coupled. Such an attempt is made by Wullens[31]. Equation (2) can be formulated in a general way for the cases that the tread is not modelled as isolated springs, as

$$\mathbf{F} = \mathbf{G}^{-1}\Delta\mathbf{y} \qquad (4)$$

In this case $\mathbf{G}$ is the sensitivity matrix describing how strong the reaction at different positions is due to a force applied at a certain position. Since the matrix has to be inverted only those points can be considered which actually are in contact. Unfortunately this is not known from the beginning and therefore an iterative process has to be carried out to find the correct solution of the force distribution. This iteration process will deliver the correct contact geometry and the correct contact forces for each time step. There are different possibilities to model $\mathbf{G}$, e.g. as deformation of an elastic half space or from the deformation of an elastic layer of finite thickness. In the second case Larsson's tyre model[12] could be used. The contact forces will be applied to calculate the vibrations of the tyre structure. The exact contact geometry is the key to the air-pumping description.

Considering that the contact geometry is time varying, it is clear that models based on steady state description of the rolling tyre (where after calculating the contact geometry once, random forces are applied to the tyre structure in the contact area), can only work when the roughness is very small. Variation of the total normal contact force observed in calculation can easily exceed 10% of the total load force and the contact area is varying substantially over time.

The difficulties in practice are to find sufficient good input data both on the material side (e.g. rubber data under deformation, temperature dependent, etc.) and the exact geometry, i.e. roughness of the ground. Substantial work remains in order to achieve good simulation tools.

2.4 Radiation Model

The last step is to calculate the radiated sound caused by the vibration of the tyre structure and the variation of the geometry between tread and road surface.
Assuming to have a perfect model describing exactly the motion of the tyre and the surrounding medium during rolling, one would be able to predict the sound pressure due to the rolling process. However, the models are not perfect. Tyre vibrations can certainly be predicted with highest accuracy. Air-pumping on the other side demands not only knowledge of the deformation of the tyre in the contact area but also of details such as flow resistance of the road surface, interaction between tread pattern, etc.. That the tyre and road build a horn-like geometry, which leads to a substantial amplification of sound radiated from the contact, makes the situation even further confusing. The so-called horn effect is a substantial factor when reducing tyre/road noise by absorbing road surfaces. When predicting tyre/road noise, therefore the horn effect has to be included.
There are several ways to calculate the radiation from tyres, one could apply Boundary Element Methods[32], Infinite Finite Elements[33] or ray tracing[34]. One possible idea would also be the multipole synthesis. There, two multipoles are situated symmetrically on either side of the surface. Thus the boundary condition of the surface - given in the form of the reflection factor in the normal direction of the surface - can easily be satisfied. The key point is that both multipoles together have to fulfil the boundary condition given on the surface of the tyre (i.e. the calculated velocity in the normal direction of the tyre surface). In this way the multiple reflection of sound in the horn is considered. A more complete description of this method applied to the problem is given in the literature[35].
Concerning the complexity of the tyre/road noise radiation, one expects that combined approaches including, FE and for instance ray tracing might have the highest potential, especially when taking into account reflections by the car body.

3 TYRE/ROAD NOISE GENERATION

Experiments also give the opportunity to learn from reality by comparing theory and experiment and in this way to improve the understanding. Concerning tyre/road noise generation most of the experimental work found in the literature considers the measurement of sound pressure for different road/tyre combinations as function of driving speed, load, etc.. The main problem with these measurements is that one is forced to draw conclusions from the radiated sound pressure concerning the tyre/road interaction. This often appears to be difficult, especially due to the problem’s complexity and the lack of knowledge and understanding. That we measure mainly sound pressure levels, however, is due to the fact that it is extremely difficult to measure contact forces, which would be much easier to interpret. Most favourable would be to measure contact forces as function of time and space with a sufficiently high resolution. This would allow for studying the influence of road and tyre parameters on the interaction of tyre and road surface and in this way on the tyre/road noise generation. However, such measurements seem not to be feasible with today’s techniques. As a consequence one has to rely on the results from models to gain improved understanding. This demands that the models are well validated and that the user is aware of the limitations of the models in order to exclude misinterpretations. At the Department of Applied Acoustics, Chalmers University of Technology, an acoustic rolling model is under development[40,31]. The model is based on work by Kropp[36]. Similar approaches have later been implemented by Hamet[41] and others. The rolling model follows in general the outline described in the previous text, but will not be presented in more detail in the following. Instead a short validation of the model will be presented and some results will be discussed.

3.1 Validation of the Acoustic Rolling Model

Since contact forces are not available, a validation of the rolling model is best carried out by measurements of the tyre vibrations. This can be done by measurements with a Laser Doppler Vibrometer. In this way one measures directly the vibrations responsible for the sound radiation from the tyre. However one would not gain any information concerning the vibrations directly in the contact patch, since it is not possible to measure there. An alternative is to use accelerometers placed in between the tread blocks. In this way one can even observe the tyre vibrations when the accelerometer passes through the contact area. Since the measurements are carried out in the coordinate system fixed to the rotating tyre, the measurements have the disadvantage that they are influence by the Doppler effect (from the accelerometer's point of view, the contact forces are moving). This also means that measurements do not characterise directly the vibration responsible for the radiation of the tyre.
For the validation presented in the following, results from measurements with accelerometers are shown and compared with calculations. Measurements were carried out on a tyre rolling on a test drum with an ISO surface replica. Tyres with circumferential grooves and a tyre with cross bars were used (see Figure 5). Mobility measurements on the tyres were used to update the tyre model (in the cases presented in the following the model of the orthotropic plate was used).

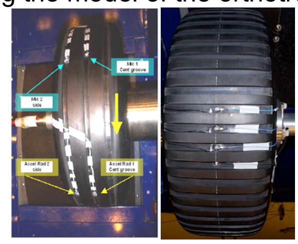

Figure 5: Tyres used for the validation; left: tyre with circumferential grooves (arrows point on accelerometers), right: tyre with crossbars.

As input data for the contact model the tyre tread surfaces and the road surface geometry are needed. For this reason the tyre surfaces were scanned and the information was discretised into 15 parallel tracks over the tyre width (in this case 15 cm) and into 512 slices around the circumference (the resolution is then about 3.5 mm). The data for the road replica were obtained by laser measurements made on 15 parallel tracks 1 cm distant from each other. The roughness amplitude is measured every 0.2 mm and resampled to match the resolution in the circumferential direction of the tyres. With these input data the dynamic contact forces can be calculated according to Equations (1) to (4). For the characterisation of the tread an elastic half space is used[41]. From the contact forces the acceleration of the tyre structure and the deformation of the tread can be calculated.
Figure 6 shows as an example the comparison between measured and calculated acceleration for one single revolution of the tyre. Although both results show a surprising degree of similarity, such comparisons are very difficult to carry out, since one does not know at which position of the ground the tyre is when evaluating the acceleration for one rotation. Therefore a comparison of the average over several rotations is used in the following.

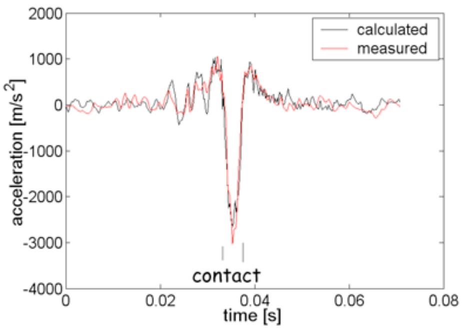

Figure 6: Comparison between measured and calculated acceleration for a single revolution of the tyre with circumferential grooves running on an ISO surface with 80 km/h and a load of 300 kg.

Figure 7 shows the comparison between the measured and calculated acceleration averaged over a number of revolutions. The agreement is quite good both for the tyre with circumferential grooves and for the tyre with crossbars, and based on this good agreement one might use the simulation model to improve the understanding of the interaction between tyre and road.

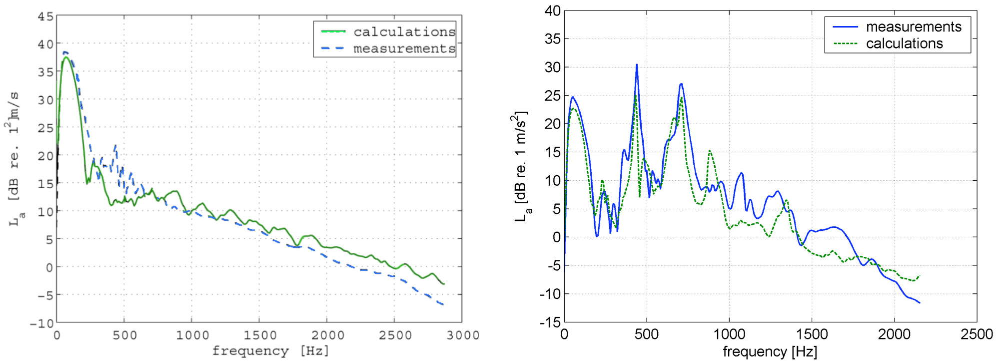

Figure 7: Comparison between measured and calculated acceleration signals on the tyre structure: tyre with circumferential grooves rolling on ISO road at 80 km/h (left), crossbar tyre rolling on ISO road at 60 km/h (right)

3.2 Interpretation of Results from the Rolling Model

From the previous Figures one can already draw some conclusions. The results in Figure 6 show nicely how the position where the accelerometer is mounted is accelerated when approaching the contact area. It also shows that the highest amplitudes are located around the contact area while far away from the contact the vibrations are much lower and mainly contain lower frequencies. Even in the contact itself vibrations can be observed. How well these vibrations radiate is still one of the open questions. In the contact there is a narrow space between tyre surface and road surface. The tyre is only running on the tops of the roughness peaks which becomes obvious when inspecting a snapshot of the contact for a smooth tyre running on a ISO surface (see Figure 8).

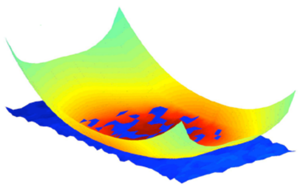

Figure 8: Calculated contact between tyre and road surface (blue colour: tyre is on the level of the road surface)

Any displacement of air due to vibration or aerodynamic sources in the contact has to pass this narrow gap between tyre and road. It is obvious that both the surface properties, the exact shape of the contact path and the tread pattern geometry will influence the radiation of sound due to events in the contact area. At the same time sources located at the border of the contact patch can be considered as very efficient due to the horn effect.

The time varying contact forces excite tyre vibrations. Figure 9 shows the vibrations of the tyre in the coordinate system of an exterior observer for three different frequencies. Again it is visible that the highest vibration amplitudes are located around the contact area. At the same time one might be surprised that with some distance from the contact there are only plane waves observed. The main questions arise which of the vibrations visible on the tyre structure are responsible for the radiation. Studying the radiation from cylinders one comes to the conclusion that most of the circumferential modes on the tyre are actually (fortunately) very inefficient radiators. The radiation efficiency is increased by the horn effect.

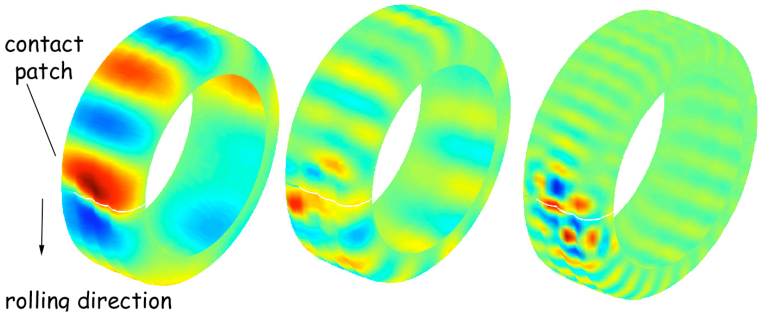

Figure 9: Calculated vibration of the tyre for 125 Hz (left), 500 Hz and 1500 Hz.

Figure 10 shows the radiation efficiencies for the first 20 circumferential modes with and without the influence of the horn effect.

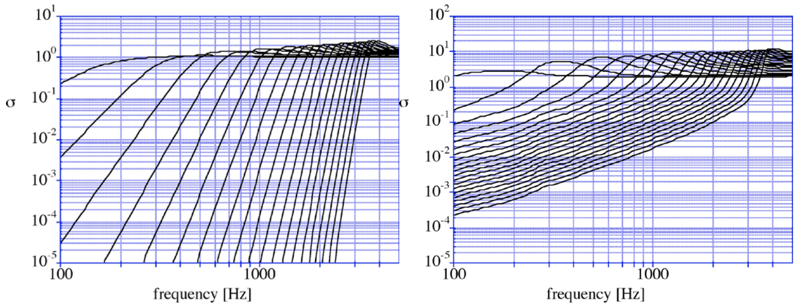

Figure 10: Radiation efficiency of the first 20 circumferential modes (order n=0–19) for a freely suspended cylinder (left) and a cylinder on a rigid ground (right)

From Figure 10 it is obvious that low order modes are radiating much better in the frequency range of interest than high order modes. The question arises how strongly these low order modes are excited. This is difficult to conclude from Figure 9 where a linear scale for the vibration amplitude is used. Therefore the wavenumber spectrum is calculated for the middle track of the tyre. The spectrum is shown in Figure 11 (left) as a function of frequency and wavenumber. The spectrum shows a maximum for the free waves (bending waves following the square root of frequency) but also a substantial part of energy distributed to other wavenumbers due to the forced excitation in the contact. The analysis of the wavenumber spectra for selected frequencies (Figure11, right) shows this even more clearly. The Figure also reveals the presence of wave components with lower wavenumbers even though somewhat lower in amplitude. From the radiation efficiencies shown in Figure 10 it is obvious that although the amplitudes of these wave components are lower they will contribute substantially to the radiation from the tyre surface.

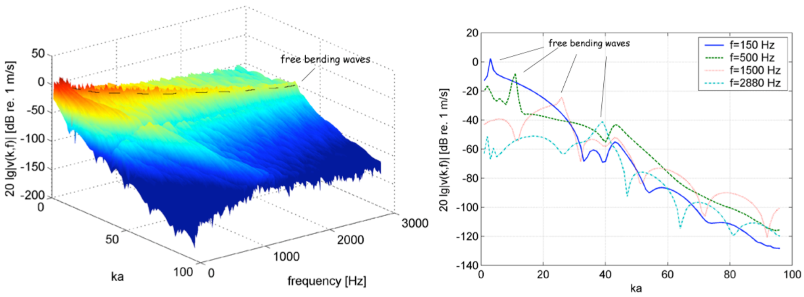

Figure 11; Spectrum visa wavenumber (a is the radius of the tyre) and frequency for the vibration on a track around the circumference of the tyre (left) and the wavenumber spectrum for some selected frequencies (right)

At 500 Hz for example the main contribution in the wavenumber spectrum corresponds to a normalised wave number of about 10. The radiation efficiency for this wave number is at the same time about 20 dB below the radiation efficiency of low order modes.

4 CONCLUSIONS

A rolling model was presented and one result from this model was discussed. It shows that the generation of tyre/road noise due to the vibration of the tyre structure is not only due to the radiation from free waves but also due to the forced excitation of low order modes. The excitation of the low order modes by the time varying contact forces can be interpreted as a time varying contact area which also can be observed in the analysis of the contact geometry. From these results one could draw the conclusion that in order to reduce tyre/road noise, the main goal has not to be to reduce the vibration of the tyre structure, but to distribute the unavoidable vibrational energy in such a way that modes are excited, which have low radiation efficiency. One key to this is certainly to take care by means of tyre and road surface design that the contact area is changing as little as possible and that unavoidable changes will take place smoothly. Such a design, however, demands a sound understanding of the interaction between tyre and road. Additional one has to be aware that other source mechanisms will limit the improvement.

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