Quantification of the Equivalent Sources of Different Tire Noise Models by means of the ASQ technique

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Introduction

Tire noise has become a major noise contributor in many traffic situations nowadays. Determining the specific contribution of tire noise to the human perception of a complete sound event (such as e.g. a car pass-by) remains however very difficult due to the strong dependency of many contributing sources (engine, exhaust, tire. . .) on a variety of factors such as operating conditions, road surface and acoustic environment. The complex masking phenomena that occur in the human hearing prevent all sources from being audible at all times and small changes to a single (sub-) source or transfer path can often completely change the perception of the sound event.

Identifying the most annoying sound (sub-) source in a complex sound event is in general very difficult unless one can really listen to the sound event. In order to allow quick and economic investigation of the impact of possible changes to (sub-) sources, OEM's are more and more interested in models that can auralize the complete sound event (i.e. such that a real listening experience becomes possible), in order to allocate the available resources for treating the most annoying sub-source or related transfer paths. In this way, noise levels can be lowered or the quality of the sound event can be improved [1].

For reasons of computational efficiency and adaptability of the models, most auralization models work partially in the frequency domain. The time-frequency spectrum that occurs at the receiver position is first modeled by means of a *source - transmission path - receiver* model which involves the modeling of all noise sources and the determination of all relevant transfer paths. The work described in this paper is situated in this first phase. In a second phase, out of scope of this paper, the predicted time-frequency spectrum is reconverted back to the time-domain.

The specific nature of a rolling tire makes locating and quantifying the different sub-sources on the tire an inherent difficult task. The sources are thought to be numerous and complex, with their relative magnitudes changing with tire-road specifications and operating conditions [2]. Direct measurement techniques with e.g. accelerometers are impossible or very difficult, time consuming and expensive in practice. Indirect techniques such as sound intensity techniques or airborne source quantification are therefore preferred. The latter was selected here, as in [4].

In view of real-time implementations of the auralization models, it is essential to keep the calculation efforts (and hence the amount of sub-sources under consideration) as low as possible. Different tire models with an increasing amount of defined sub-sources are investigated here. The goal of this research is identifying the amount of sub-sources needed to come to a suitable tire noise model, depending on the desired prediction accuracy. Moreover, the quantification of these sub-sources is investigated.

Airborne Source Quantification

Airborne source quantification (ASQ), often named acoustical transfer path analysis, is a well known procedure which allows to trace the flow of acoustical energy from a noise source, through a set of airborne pathways, to a given receiver location. Figure 1 gives a schematic overview of an ASQ set-up for tire noise.

The acoustical pressure P_j at a receiver location j can be written as the sum of N partial pressures P_{ij}, originating from the N different sub-sources i on the rolling tire, see equation 1. Parts of the leading edge, trailing edge, outer and inner sidewall are typically considered to be sub-sources of the rotating tire, see further.

$$P_j = \sum_{i=1}^{N} P_{ij} = \sum_{i=1}^{N} Q_i H_{ij} \qquad (1)$$

Each partial pressure P_{ij} is defined by the product of the source strength Q_i of sub-source i, and the corresponding acoustical frequency response function H_{ij}, see equation 1. The source strength is expressed in terms of the volume velocity Q_i, since this is a stable quantifier (under different acoustic environments) that suits the transfer path approach very well.

$$[Q] = [H_{near}]^+ \cdot [P_{indicator}] \qquad (2)$$

$$[P_{receiver}] = [H_{receiver}] \cdot [Q] \qquad (3)$$

For a rotating tire, the unknown, complex source strength's Q_i are found by means of an inverse ASQ procedure, based on indicator microphones ($P_{indicator}$) close to the rolling tire, see equation 2 and Figure 1. In a next step, these source strength's Q_i serve to calculate the spectrum at any receiver position with a normal ASQ, as in equation 3.

Since the matrix $[H_{near}]$ is not square, a Moore-Penrose pseudo-inverse is calculated. When the amount of

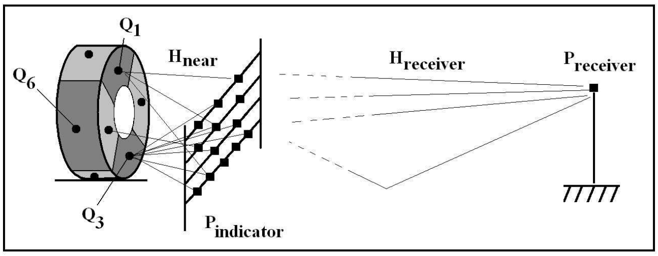

Figure 1: Indicator pressures are used to determine the source strength's Q_i by means of an inverse ASQ. Next, the spectrum at the receiver is calculated by a normal ASQ.

unknown source strengths Q_i is large in comparison with the amount of indicator microphones, this inversion becomes badly conditioned. Tikhonov regularization is often used to add a side constraint, i.e. a smoothness property, on the solution sought. The regularized Tikhonov solution Q_{reg} is found by minimizing the error criterion defined by equation 4. The regularization parameter β weights the importance of the residual norm, respectively the smoothing operator in the error criterion. The parameter β is found by means of the L-curve criterion, i.e. in the corner of the plot of the regularized solution η (equation 5) versus the corresponding residual norm ρ (equation 5), for different values of β.

$$J = ||HQ - P||^2 + \beta||LQ||^2 \qquad (4)$$

$$\eta = ||Q_{reg}||, \qquad \rho = ||H_{near}Q_{reg} - p_{indicator}|| \qquad (5)$$

Tire noise models under investigation

In view of a possible real-time implementation of the auralization procedure, it is important to keep the complexity (and hence the calculation times) of the procedure as low as possible. In practice, this means that the number of sub-sources that is considered should be limited.

In this paper, the results are presented for 12 different models. The amount and position of sub-sources differs in the different models, see Figure 2 and table 1. Each picture represents the tread (TR) and the outer sidewall (OS). No sub-sources were assumed on the inner sidewall here, since it was assumed that the radiation from this region did not contribute significantly to the sound pressure at the selected receiver point, located on the rolling axis of the tire, at a distance of 4 [m] in front of the outer sidewall, 1.2 [m] above the floor.

Because of the large size of some of the patches belonging to a sub-source, especially for the models with only a few sub-sources, the acoustic transfer paths between the receiver point and the surface patch cannot be approximated by the transfer path between the receiver point and a single monopole point source placed in the center of the patch. In total, the acoustic FRF's were measured towards approximately 150 points spread over the tire surface. The acoustical FRF's between the receiver and a sub-source are calculated by averaging the FRF's between the receiver and all points on the respective sub-surface.

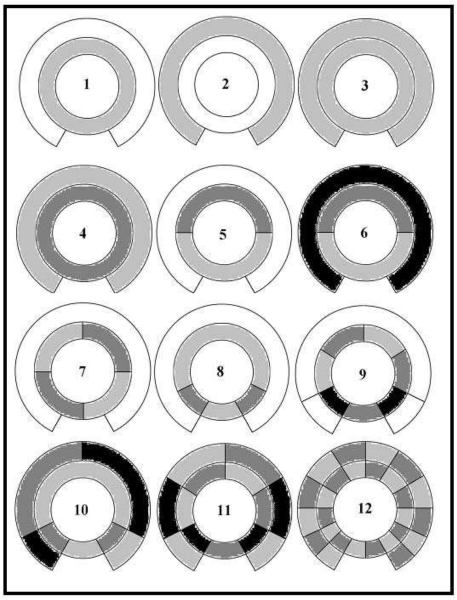

Figure 2: Different tire noise models under investigation

Mod.	Tot.	OS	Tr.	Mod.	Tot.	OS	Tr.
1	1	1	0	7	4	4	0
2	1	0	1	8	4	4	0
3	1	1		9	7	7	0
4	2	1	1	10	8	4	4
5	2	2	0	11	13	7	6
6	3	2	1	12	26	14	12

Table 1: Overview of the sub-sources considered in the different tire models (Model, Total, Outer Sidewall, Tread).

Measurement set-up

A radial winter tire type 205/55 R16 was used for all measurements. The measurements were performed on a safety walk (low texture) and Glenn Eagle (rough) road surface at a Goodyear test facility inside a semianechoic room, see Figure 3. The tire was preloaded with 3040 [N], and the tire pressure was 2.1 [bar] for the unloaded tire. The tire had a warm up time of 10 minutes, rolling at 80 [km/h]. This speed was held constant during all tests.

A rack with 42 indicator microphones, used for the quantification of the N source strengths Q_i of the sub-sources, was placed in front of the rolling tire as shown in Figure 3. The majority of the microphones are placed close to the ground, since most tire noise generating phenomena are located in that region. The minimal distance between the microphones and the tire is 0.14 [m].

All transfer paths H_{ij} were measured with a calibrated volume velocity source mounted on the non-operating tire on the drum, see Figure 3. The transfer paths towards the indicator microphones and the microphone at the receiver location were measured simultaneously,

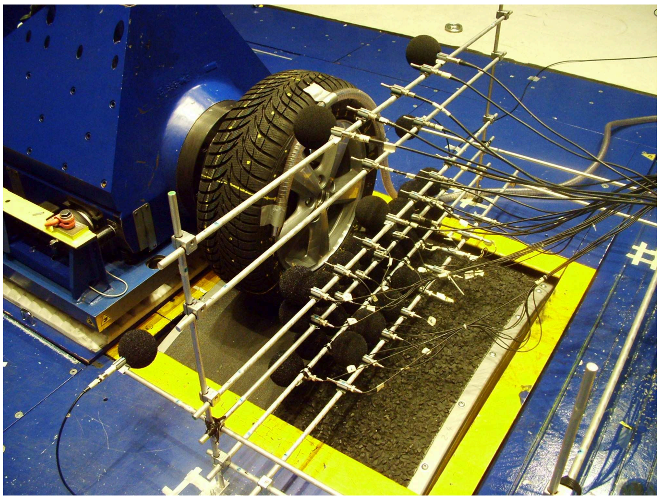

Figure 3: Measurement set-up in a semi-anechoic room; calibrated volume velocity source is mounted on the tire.

in a direct way (i.e. non reciprocal) because of practical considerations. Below 200Hz, the source output is too low to allow accurate measurements of the transfer paths. Since tire noise below 200Hz does not contribute significantly to the overall sound quality perception of tire noise, this frequency range was not consider further here.

Evaluation

The performance of the different tire noise models under investigation is compared by plotting the prediction error between measured and predicted $1/3^{rd}$ octave band levels at the selected receiver location. Figure 4 shows the results for the tire rolling on the low texture road, while Figure 5 shows the results for the tire rolling on the rough road. Octave band number 23 has its center frequency around 200 [Hz], band number [39] has its center frequency around [8000Hz].

For most of the discussed models, the number of sub-sources remains small in comparison to the amount of indicators (i.e. 42) that was used here. The matrix that has to be inverted is therefore relatively well conditioned, such that regularization does not improve the quantification process. The discussed Tikhonov regularization was only beneficial for model 12, such that only for this model the Tikhonov regularized solution is shown. For models 1 to 11, the unregularized solutions are shown.

Besides the L-curve criterion, the Generalized Cross Validation, well-known from literature [3], was also briefly investigated here as a parameter selection criterion. Earlier findings of Kim and Schumacher were hereby confirmed. Kim [5] stated that the L-curve is more effective compared to GCV in cases were the problem is still relatively well conditioned. Schumacher [6] reported the superiority of the L-curve over the GCV in industrial applications. In the present findings, the errors on the $1/3^{rd}$ octave band levels were several dB higher in case the GCV criterion was used. Therefore, for model 12, the Tikhonov regularized solutions based on the L-curve are shown in all figures.

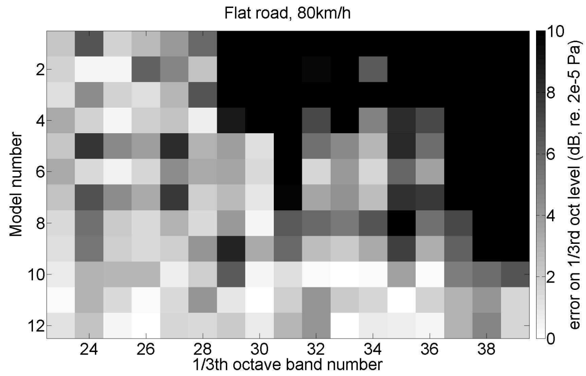

Figure 4: Error on $1/3^{rd}$ octave band level for each of the 12 considered models, low texture road, 80 [km/h].

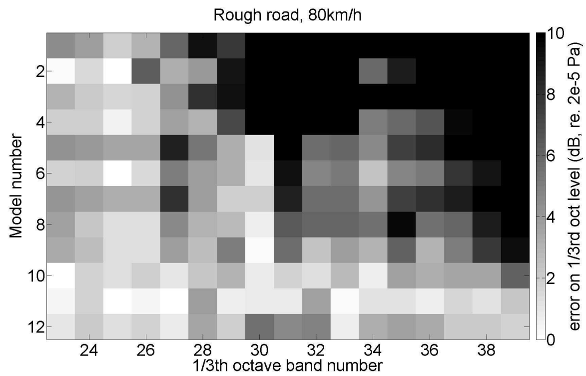

Figure 5: Error on $1/3^{rd}$ octave band level for each of the 12 considered models, rough road, 80 [km/h].

It is clear from Figures 4 and 5 how the accuracy of the models increases drastically when the number of sub-sources increases (from top to bottom). The frequency up to which the predictions are accurate also increases steadily and hence, a diagonal effect is visible in the figures. Moreover, the results are very similar for both road surfaces.

As an example, Figures 6 and 7 show some representative results for model 11, considering 13 sub-sources on the tire. For the tire rolling on the low texture road surface, the effect of air pumping is dominant and the resulting spectrum contains many peaks as can be seen in both figures. On the rough road surface however, the resulting spectrum is much more flat.

$$\text{Sound Power, W} = \rho c|Q|^2 k^2/8\pi \tag{6}$$

$$\text{Sound Power Level, PWL} = 10log_{10}(\frac{W}{10^{-12}})dB \tag{7}$$

The relative strength of the different sub-sources that are defined on the tire can be presented by means of the radiated sound power W. The radiated sound power W $[kgm^2s^{-3}]$ of a monopole in free field is given by equation 6, with ρ $[kgm^{-3}]$ the density of the propagating medium. The sound power level PWL is then given by equation 7. Figure 8 shows the sound power levels, resulting form the calculations for model 11. It is clear that most of the sound energy is located near the contact patch, especially at the trailing edge (i.e. the left hand side). The high values on the upper side of the tread are probably due to the fact that no sub-sources were defined on the rear side of the tire (i.e. the inner sidewall).

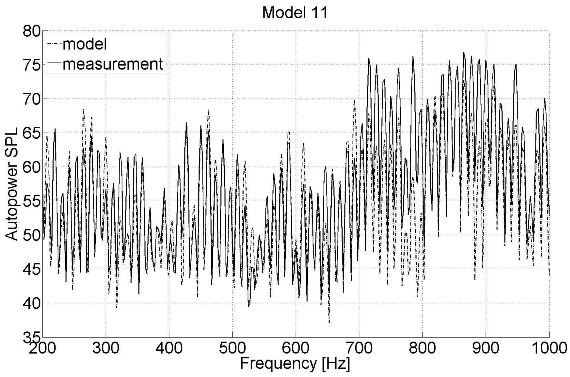

Figure 6: Measured and predicted autopower SPL, model 11, low texture road, 80 [km/h], 200 [Hz]-1000 [Hz].

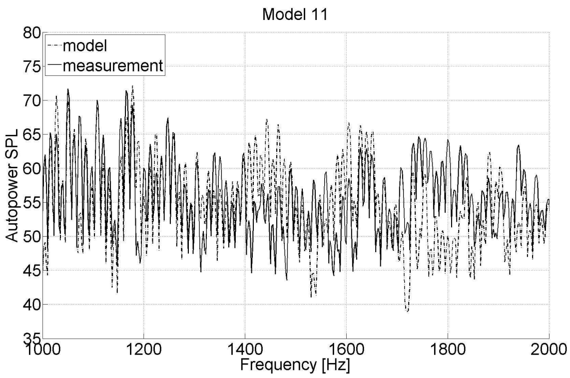

Figure 7: Measured and predicted autopower SPL, model 11, low texture road, 80 [km/h], 1000 [Hz]-2000 [Hz].

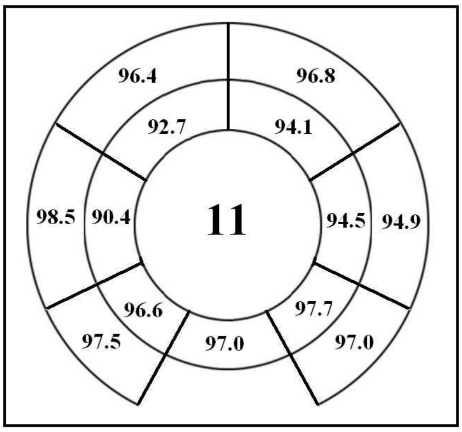

Figure 8: Relative source strengths (sound power level), model 11, low texture road.

Conclusions

In this paper, it was shortly shown how the ASQ technique was incorporated in the first phase of a complete tire noise auralization model. The strengths Q_i of all defined sub-sources on the tire were found by means of an inverse ASQ method. Based on the calculated source strengths, the spectrum at a target point was predicted with a forward ASQ.

By means of the complete auralization model, one is able to evaluate changes to the tire profile, road surface, transfer paths... by means of a real listening experience. So called "what-if " games can reveal the impact of possible noise treatments on the human perception of the sound.

It was shown how reducing the model complexity results in lower accuracy of the models at higher frequencies. Depending on the required accuracy, a suitable tire model can be selected.

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