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Tyre/road noise models in the last two decades: a critical evaluation

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Abstract

During the last two decades, various efforts have been made to model, with a certain degree of physical abstraction, the noise generated by the interaction between a rolling tyre and the road surface. Without the intention of being complete, we have tried to situate a selection of these models in the research field of tyre/road noise by making a critical evaluation. First, an overview of various tyre/road noise mechanisms is given. Then, an assessment of the tyre/road noise models is made in terms of modelled noise generation mechanisms, frequency range, speed exponents, experimental validation etc. With this paper we try to facilitate a new discussion about what issues are considered to be the most important for future tyre/road noise models.

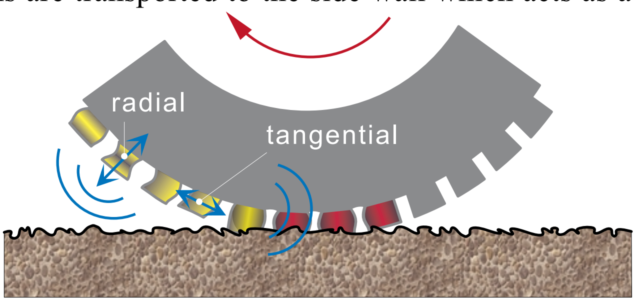
1. Overview of tyre/road noise generation mechanisms

Many physical processes are considered to play a role in the generation of tyre/road noise. In the literature however, there is no clear consensus about the relative contribution of these various mechanisms, except for the important contribution of radial tyre tread vibrations in the generation of rolling noise. This makes mathematical modelling of these tyre/road noise generation mechanisms a challenging but complex task. In general, the mechanisms are divided in two groups: mechanical and aerodynamical mechanisms.

Mechanical mechanisms

Radial and tangential vibrations of the tyre. Radial vibrations of the tyre belt and of the profile elements are excited by road roughness elements deforming the tread or by tread elements hitting (on the leading edge) or leaving (on the trailing edge) the road surface. Tangential vibrations are excited by tangential forces in the contact patch.

Side wall vibrations. The tread vibrations are transported to the side wall which acts as a ‘sounding board’ and radiates sound.



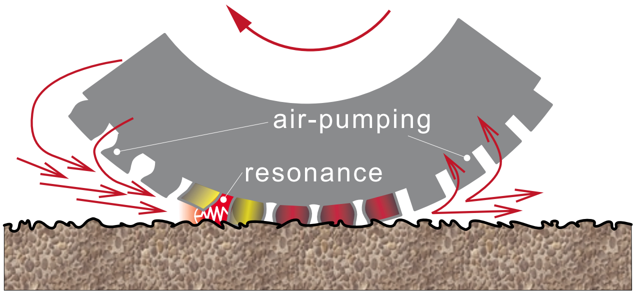
Stick-slip. Stick-slip vibrations are a result of the stick-slip phenomenon that occurs in the case when materials exhibit reduced friction with an increase in their relative speed (negative friction gradient). So, the tread blocks of the tyre alternately ‘stick’ and ‘slip’ relative to the road surface. The stick-slip mechanism is normally associated with situations where relatively high tangential forces are applied to the tyre (e.g. acceleration, breaking, cornering). The role of this mechanism for free rolling conditions is unclear.

Adhesion stick-snap. Stick-snap occurs when the tyre tread surface gets sticky (for example ‘winter’ tread compounds at high temperature) and the road surface is very clean. Also, tyres may stick to hot asphalt road surfaces. In those cases the adhesive bond strength is increased which leads to an increase of the excitation at the trailing edge of the tyre footprint.

Aerodynamic mechanisms

Cavity resonance in tyre tube. Resonances in the cavity inside the tyre-wheel assembly are known to contribute to the noise generated by the tyres. These resonances are prominent at discontinuities like bridge transitions and railway crossings but not for a free rolling tyre.

Air-pumping. A rolling tyre displaces air from the tyre when it deforms entering the contact patch region. Subsequently it returns air to the tyre tread and roadway cavities as the tyre tread goes back to the undeformed state when it leaves the contact region. This pumping of air causes sound production.



Air resonant radiation. Helmholtz resonances can occur at the trailing egde of the tyre. The cavity for the Helmholtz resonator is formed by the groove releasing the contact with the road surface and acts as spring. The air present between tread and road surface is the neck of the resonator and acts as a mass.

Pipe resonance. Each tread pattern, in contact with a rather smooth road surface, constitutes a system of pipe resonators. Their resonant frequencies depend on the geometrical properties but not on the rotation speed of the wheel.

Frequencies and speed exponents

The various mechanisms that play a role in the generation of tyre road noise affect a different part of the total tyre/road noise spectrum and their relative importance for the spectrum changes with speed. Therefore, we can define a frequency region and speed exponent k for each mechanism. With the speed exponent k the variation of the (spectral) sound level can be expressed as

$$L_p \sim 10 \cdot \log(v / v_0)^k [\mathrm{dB}] = k \cdot 10 \cdot \log(v / v_0)[\mathrm{dB}]. \qquad (1)$$

Figure 1, which is based on literature research presented in [1], gives an overview of the speed exponents and frequency ranges for the various mechanisms.

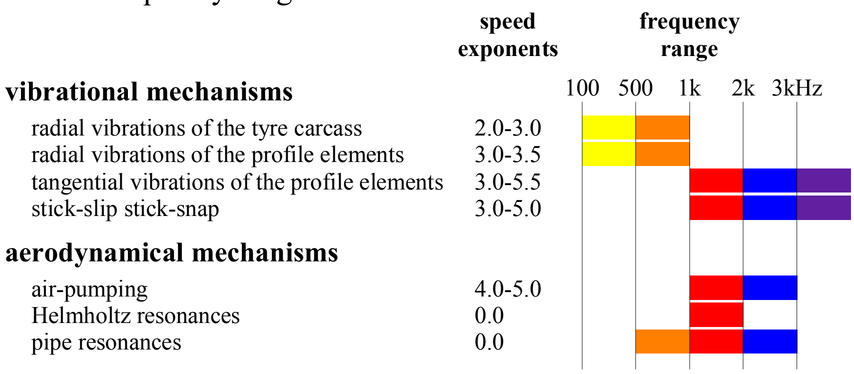


Figure 1: Overview of speed exponents and frequency ranges for tyre/road noise generation mechanisms.

Clearly, the radial vibrations are the cause of low frequency (< 1 kHz) noise. However, the high frequency noise is caused by a combination of many different noise generation mechanisms. This makes mathematical modelling of the noise generation a complex task.

2. Tyre/road noise models

In the last decades, various attempts have been made to model (aspects of) the tyre/road noise generation mechanisms. It is impossible to review every paper on this subject. We have limited this review to models that try to predict sound levels based on road and tyre data input. Furthermore, we have tried to make a selection of models that shows the diversity in modelling approach and results.

The modelling approach used in various projects can be classified in three categories: purely statistical models, purely deterministic models and hybrid models. The purely statistical models try to relate measurement data to measured sound production. A well-known example of this approach is the work of Sandberg and Descornet [2]. Purely deterministic models try to model the physical processes involved in tyre vibration and sound radiation from the tyre. Measurement data is only used for the validation of the model. The tyre model of Kropp [3,4,5] is an influential example of this modelling approach. Lately, a combination of statistical and physical modelling is increasingly used: the hybrid modeling approach which was used by Fong [6], Hamet et al. [7], and Beckenbauer and Kuijpers [8] all these models are based on the contact force calculation method introduced by Clapp [9].

An overview of the relevant models that have been published in the literature the last years is given in Table 1. All these models have in common that they try to describe the total path from road surface characteristics to noise production. Besides these, there are a considerable amount of models that only describe a part of this total path like for instance tyre vibrations or the horn effect. These models could be used as building blocks for future full-scale models but are not discussed here.

3. Discussion

For a fair comparison of the tyre/road noise models it is important to distinguish between their objectives. There are models that try to explain tyre influence and models that explain road influence on the tyre/road noise. All three physical models focus on the tyre influence while the other models focus mainly on the road influence. This means that to use the physical models, one needs more information about the tyre properties, in contrast with the statistical models that treat the tyre as a “black box”. The hybrid models try to find a compromise between the level of detail in tyre and road model parts.

The field of application of these models is closely related their objective. Roughly speaking, the physical models can be applied for tyre design, the statistical models are focussed on road design and the hybrid models focus on the optimization of the combination of tyre and road. Therefore, at present, it seems to be inadequate to apply a physical model for road design and a statistical model for tyre design.

In this comparison of models, it is difficult to evaluate the expected accuracy of the results of the models. The reasons for this are the different model objectives and the lack of validation of some of them. It seems fair to say that the current status of the physical models is such that they are mainly suited to investigate the noise generation mechanisms and to make qualitative design studies. Quantitative results are not reliable yet. The statistical models seem to have a higher degree of quantitative accuracy. However, the parameters in these models are normally not real physical parameters but derived parameters such as a texture spectrum. This means that the results of parameter studies have to be translated back to

model name or author	modelling approach	mechanisms	used techniques	assumptions	parameters	results	validation	future developments	ref.
Kropp	physical	radial vibration, 2D sound radiation with horn effect, sound absorption	analytical model of supported plate, sound source superposition	slick tyre	tyre material properties, road profile	sound spectrum in plane of tyre	drum measure-ments in plane of tyre	tangential vibrations, multiple tyre material layers	[3]
TRIAS	physical	radial tyre vibration, air-pumping, 2D sound radiation with horn effect, sound absorption	vibration model similar to Kropp extended to 2D, extension for air-pumping noise, sound radiation with 3D BEM, propagation over (porous) surface	slick tyre for vibration calculation but groove pattern is used to predict air-pumping noise	tyre material properties, tyre profile information, road profile, road absorption characteristics	pass-by sound spectrum	not (yet) published	validation, improved radiation model	[10]
Bremner/ Huff/ Bolton	physical	tyre vibrations, sound radiation	Statistical Energy Analysis (SEA) with orthotropic cylindrical shell vibration and sound radiation	Tyre vibrates as an infinite cyl. shell and radiates as a flat plate in a baffle.	multilayer tyre material properties	sound spectrum at 7.5m distance	validation made on dispersion character-istics		[12]
Sandberg/ Descornet	statistical	low frequency (vibration), high frequency (air-pumping)	cross correlation of texture spectra with sound spectra	based on 49 (dense) pavements with 4 tyre types	texture spectrum	pass-by sound spectrum	statistical model based on measure-ments		[2]
TINO	statistical	all mechanisms induced by the road texture	cross correlation of texture index with sound level	based on 7 (dense) pavements with 1 tyre type	texture index (derived from texture spectrum)	pass-by sound level	statistical model based on measure-ments		[11]

model name or author	**modelling approach**	**mechanisms**	**used techniques**	**assumptions**	**parameters**	**results**	**validation**	**future developmentss**	**ref.**
Fong	hybrid	all mechanisms induced by the contact pressure on the tyre	determination of transfer function between contact pressure spectrum and nearfield sound intensity, 2D contact pressure model	transfer function from contact pressure to sound only depends on tyre, not on road surface	tyre stiffness, road profile	near-field sound spectrum	transfer functions based on measure-ments		[6]
PREDIT	hybrid	all mechanisms induced by the contact pressure on the tyre	cross correlation of contact pressure spectrum and pass-by/nearfield sound spectra	??	tyre stiffness, road profile	??	not (yet) published	validation in progress	[7]
SI.R.U.US	hybrid	all mechanisms induced by the contact pressure on the tyre	contact force calculation over finite tyre width, Kropp's rolling model	??	tyre stiffness, road profile, speed	??	not (yet) published	validation in progress	[7]
SPERoN model	hybrid	all mechanisms induced by the contact pressure on the tyre	multivariate regression relating speed, contact pressure, shape factor and tyre width to pass-by sound spectra	based on 21 dense road surfaces with 14 tyre types	tyre stiffness, tyre width, road profile, shape factor, speed	coast-by sound spectrum	hybrid model based on measure-ments	3D contact, porous surfaces	[8]

physical changes, which is not always straightforward or even impossible when there are nonlinear processes active. With the hybrid models, part of these drawbacks are overcome because the relationship between physical parameters and model parameters is more explicit.

4. Outlook

Considering the recent literature and research projects, the hybrid models seem to attract more and more attention from the researchers. But there is still a lot of work to do in to improve these models. Some of the important additions that need to be considered are:

Truck tyres All the models reviewed in this article focus on passenger car tyres. However, an important part of the road traffic noise is caused by truck tyres that have a different behaviour than car tyres. The models should be extended to incorporate this tyre group.

Porous surfaces Most models focus on the noise caused by texture induced vibrations of the tyre. The growing attention for porous surfaces necessitates improvements of the models in that direction.

Mechanical impedance The dynamical properties of the road could explain the difference in tyre/road noise between concrete and asphalt roads with comparable texture. Modelling the mechanical impedance for these roads could help to explain this phenomenon.

Conclusions

An overview of the relevant tyre/road noise generation model was presented. The models were compared regarding modelled noise generation mechanisms, applied mathematical techniques, parameters, results, validation and future developments. The last years, the hybrid modelling approach seems to be favoured because it seems to be good compromise between the accuracy of statistical models and the insight that can be gained with physical models. However, without some major improvements they remain to be unsuitable for general use.

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