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Tyre/road noise prediction: A comparison between the SPERoN and HyRoNE models - Part 1

Thomas Beckenbauer[a], Philippe Klein[b], Jean-François Hamet[b] and Wolfgang Kropp[c]

[a]Müller-BBM GmbH, Robert-Koch-Straße 11, 82152 Planegg, Germany
[b]INRETS, 25 av. F. Mitterrand, case 24, 69675 Bron, France
[c]Chalmers University of Technology, Division of Applied Acoustics, SE-41296 Gothenburg, Sweden
t.beckenbauer@muellerbbm.de

The SPERoN and HyRoNE models predict the pass-by tyre/road noise of a passenger car from intrinsic characteristics of the road surface. Both models are hybrid: they combine statistical laws with physical models. With a computing time of a few minutes (very quick compared to full physical models), they provide operational tools for tyre/road noise prediction. Particular fields of interest are road surface optimisation with respect to noise at the laboratory scale, conformity of production of a new surface and acoustic monitoring of roads. They are now implemented as user-friendly stand-alone applications. The presentation will address the principles of the models, their performances and their respective main fields of application. Part 1 will address the philosophy and the principles of the models.

1 Introduction

The generation of noise due to tyre/road interaction is a complex process with several source mechanisms involved. In general two main mechanisms can be distinguished, tyre vibrations and air-flow related mechanisms such as air-pumping. Tyre vibrations occur due to any disturbance yielding time varying contact forces exciting the tyre to vibrations, which are then radiated as sound. Such disturbances can be the roughness of the road surface, the tread profile or varying properties of the tyre structure.Air flow related mechanisms consider displacement of air in the tyre/road contact due to changes in the contact geometry (e.g. closing and opening of cavities, deformation of the tyre tread, etc). The displacements or, to be more exactly, the acceleration of air leads to generation of sound.

As a consequence of their different physical characteristics tyre vibrations and air-flow related mechanisms show different dependencies on speed. Both are present over the whole frequency range. However, tyre vibration induced noise tends to dominate at lower frequencies (typically below 1 kHz) while airflow related noise tends to dominate at higher frequencies (above 1 kHz).

In order to reduce complexity, the necessity for large input parameter sets or even extensive material data and to achieve practice oriented computing times, two hybrid modelling approaches for simulation and prediction of tyre/road noise, SPERoN and HyRoNE, have been pursued by different researcher groups. The term hybrid model means the combination of physical preprocessing and conditioning of input quantities and a statistical model that is capable to adjust the model in such a way that the output represents absolute values of the target quantity.

The acronym SPERoN means **S**tatistical **P**hysical **E**xplanation of **Ro**lling **N**oise. This model is related to work performed by Chalmers and Müller-BBM within the German project "Quiet Traffic", the EC 6th framework project ITARI and the DEUFRAKO project P2RN. HyRoNE means **Hy**brid **Ro**lling **N**oise **E**stimation. The model is based on work performed by INRETS and LCPC in the French PREDIT project "Texture&Bruit" and in the DEUFRAKO project P2RN.

2 The hybrid modelling concepts

2.1 Common principles

The hybrid approaches combine a physical sub-model with a statistical sub-model. In both models the physical sub-models aim at reducing the raw texture of the road surface to the relevant roughness which is "seen" by the tyre. Both models also cover the fact, that the total tyre/road noise is due to different noise generation mechanisms. Noise from texture induced tyre vibrations as well as air flow related noise is taken into account and treated differently.

2.2 SPERoN

The main concept of the hybrid model SPERoN is based on the approach that pre-processed input data are used, which are of the same quality as one would apply in a full deterministic model simulating the rolling process in detail. Starting from the description of the road texture, i.e. a quasi 3D texture presentation within the tyre/road contact patch and of the tyre, i.e. the tension, bending stiffness in circumferential and cross direction, tread stiffness and tread pattern, the radial, uncoupled contact forces are calculated for a particular speed and tyre load [1] [2]. In Fig.1 the main structure of the model and the required input data are shown. At the moment the SPERoN model is restricted to impervious, non sound absorbing road pavements.

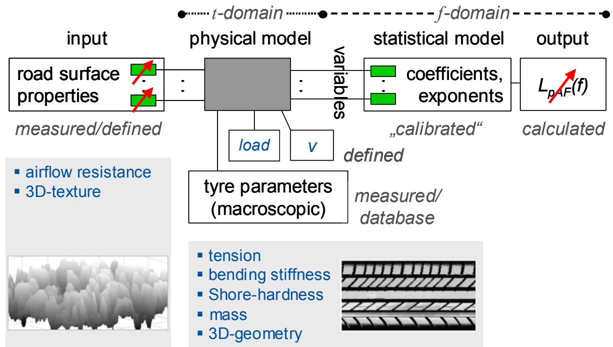

Fig.1 SPERoN structure.

The radial contact forces are calculated in the time domain which helps to cope with the highly non-linear contact problem and to ensure reasonable computing times for practical applications. The statistical sub-model is supplied with the average 3rd octave band spectrum of the contact forces which are discretely calculated in a dense grid within the tyre/road contact patch. By means of a tyre model the tyre vibrations induced by the contact forces are calculated in the time domain as well, acting as feedback onto the tyre/road contact. In Fig.2 the time history of the total normal contact force for several rolling loops starting from halt is shown. The first part is the loading process. Then the tyre starts to roll. After a few revolutions the tyre reaches a "steady state condition" and the contact force remains a function of the roughness variation in the contact only. The last part of the total contact force (150 ms) is then used to calculate the contact spectrum as shown in Fig.3.

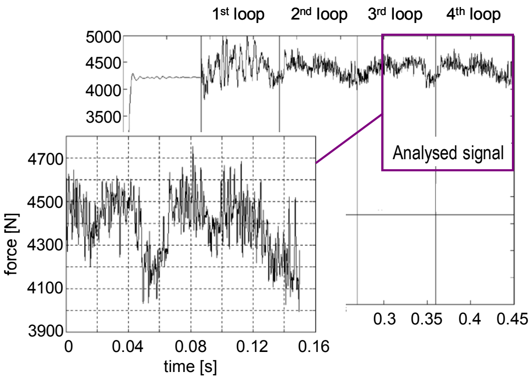

Fig.2 Total normal contact force as function of time for a particular tyre/road surface combination at a speed of 80 km/h. The evaluation of the spectrum is based on the 150 ms time interval shown in the zoomed box.

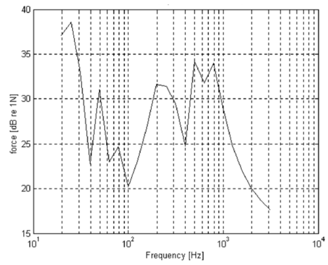

Fig.3 Contact force spectrum based on the time signal of the total normal contact force.

The statistical model is based on the assumption of noncoherent sound sources whose intensities are linearly superimposed (Eq.1). This approach agrees with the formulation and the prerequisites of a multiple regression model. Along with a component that represents the mechanically excited sound source which is driven by the contact forces p^2_{vibr} and a component which is related to air flow within the tyre/road contact patch $p^2_{airflow}$, tyre interior cavity resonances p^2_{cavity} and residual effects representing the air flow noise sources around the car body $p^2_{aerodyn}$ are taken into account. The model is capable to reproduce the absolute third octave levels of coast-by spectra for given car tyres as a function of road texture and speed. This is the output quantity of the model ($p^2_{coast-by}$). Contributions of the different components can be detected separately. The statistical model is set according to Eq.1 to 5.

$$p^2_{coast-by} = p^2_{vibr} + p^2_{airflow} + p^2_{cavity} + p^2_{aerodyn} \quad (1)$$

$$p^2_{vibr} = a\, F_c^2\, \Gamma^{\alpha_1} B^{\alpha_2} S^{\alpha_3} \quad (2)$$

$$p^2_{airflow} = b\left(F_c^2\, \Gamma^{-1.5} S^{-2}\right)^{\beta_1} B^{\alpha_2} V^4 \quad (3)$$

$$p^2_{cavity} = c\, G_{pattern}^{\gamma_1} \quad (4)$$

$$p^2_{aerodyn} = d\, V^{\delta_1} \quad (5)$$

with

- a, b, c, d regression coefficients per 3rd octave band
- $\alpha_1, \alpha_2, \alpha_3, b_1, \gamma_1, \delta_1$ exponents
- F_c contact force in N per 3rd octave band
- Γ tyre/road contact air flow resistance in Pa s/m
- B tyre width in m
- S tyre tread stiffness in N/m
- $G_{pattern}$ spectral power of the tread pattern variation
- V driving speed in m/s

In order to find out a reasonable set of coefficients and to get appropriate exponents mutiple regression analysis has been performed by means of a great deal of well documented measurement data for different road, tyre and speed combinations. These data are available from the Sperenberg project database [2] containing about 3.200 coast-by level spectra for 16 different car tyres, 38 dense and rigid road pavements and several nominal rolling speeds in the range from 50 to 120 km/h. Additionally, results of acoustic wind tunnel measurements with the vehicles used for the coast-by measurements are part of the database.

2.3 HyRoNE

In accordance with the SPERoN model the HyRoNE model relies on a linear relation between input data (contact force) and output quantity (sound pressure) as well. The HyRoNE model predicts the pass-by tyre/road noise of a passenger car depending on road surface characteristics (including possible acoustic absorption by the pavement). The prediction process distinguishes two frequency domains: the 100Hz-1250 Hz range where tyre noise is mainly attributed to radiation from the tyre belt, the range above (up to 5 kHz) where tyre noise is attributed to air-pumping phenomena.

The HyRoNe model uses two physical laws: one to take the partial contact that may occur between the tyre and the road surface into account (tyre envelopment), and one to address the noise attenuation by the road surface.

The HyRoNE statistical laws supply 1/3 octave pass-by noise levels at frequencies f_i from 1/3 octave raw or "enveloped" texture profile levels at wavelengths $\lambda_i = V / f_i$ where V is the pass-by speed.

The principle of the HyRoNE model is given in Fig.4.

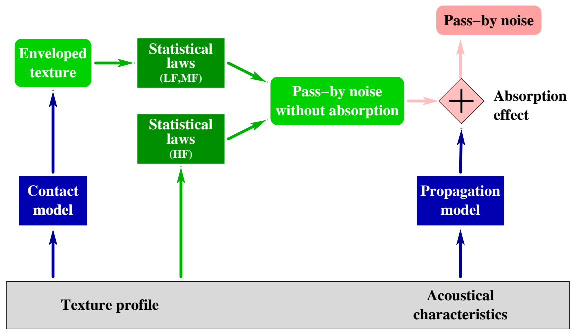

Fig.4 HyRoNE principle.

In the low and medium frequency domains, where the noise generation is mainly due to the excitation and vibration of the tyre belt, the "enveloped" texture level is used for taking the partial contact that may occur between the tyre and the road surface into account. The enveloped texture is obtained from the raw texture through an envelopment procedure applied to the texture profile. This procedure is based on a static contact model between the road profile and an elastic half space representing the tyre rubber [4] (see Fig.5). The tyre rubber is characterized by one parameter: its Young's modulus E.

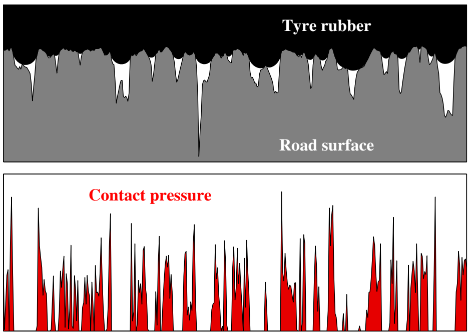

Fig.5 The envelopment procedure.

In the high frequency domain, where the noise is mainly due to the air-pumping phenomenon, the raw texture level is used for taking the possible overpressure release within the contact zone into account: laterally between the tyre belt and the road surface, if the pavement is impervious, or inside the road surface, if the pavement is porous.

The 3rd octave texture induced noise levels L_i are thus given by

$$L_i = a_i + b_i L_{eTi} \quad f_i \le 1250\,Hz$$
$$L_i = a_i + b_i L_{Ti} \quad f_i > 1250\,Hz \qquad (6)$$

The correction for a possible acoustic absorption effect is evaluated in terms of an excess attenuation. The tyre is modelled as an omni-directional point source at road surface level; the microphone is placed at 7.5 m horizontal distance and 1.2 m height (in accordance with the pass-by measurement conditions and the noise prediction configuration); the propagation is assumed to occur above homogeneous surface impedance (extended reaction), equal to the road surface impedance. The excess attenuation is provided as ΔL_{pi} for each 3rd octave f_i.

The global level $L_g^{(T)}$ predicted by HyRoNE is given by

$$L_g^{(T)} = 10\log\sum_i 10^{(L_i+\Delta L_{pi})/10} \qquad (7)$$

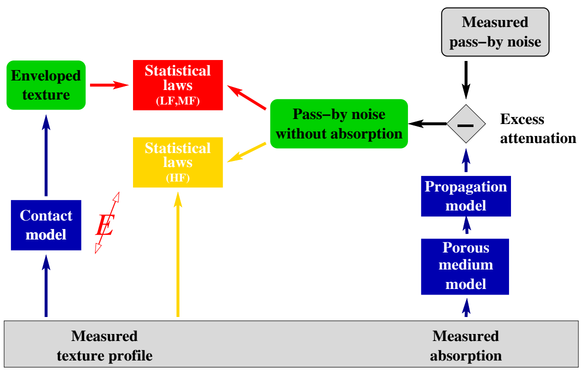

Fig.6 HyRoNE fitting.

The model construction (see Fig.6) has two objectives: to fix the optimal value of the envelopment parameter E and to determine the statistical laws between absorption corrected noise levels and texture levels in each 3rd octave band (coefficients a_i and b_i). It requires data measured on a set of road surfaces. These data consist of texture, pass-by noise and absorption measurements following defined procedures. The noise measurements are performed according to the controlled pass-by method with one vehicle/tyre combination. Texture profiles are measured at the location where noise measurements are performed. For absorbing road surfaces, the porous medium parameters are determined from normal incidence absorption coefficients measured at different locations.

3 Required input data

3.1 Road surface texture

SPERoN requires at least six 2D texture profiles of the road surface in parallel [2]. Thus, giving a quasi 3D description of the surface roughness which is sufficient as long as the texture does not show strong anisotropy. However, for anisotropic surfaces the number of measured profiles simply has to be increased to ensure a good description of the lateral roughness distribution.. The profiles must at least cover a length of 2 m for passenger car tyres which agrees with the circumference of a normal car tyre. The six profiles should cover the typical width of the tyre/road contact patch, i.e. 100 mm. The resolution of the texture data must be high enough to cover a texture wavelength range beginning at 1 mm. The roughness depth must be normalized in such a way that, regarding all texture profiles, the overall roughness peak determines the zero value. All other roughness values of the six profiles are given in relation to this overall peak.

HyRoNE requires 2D texture profiles. Its construction was performed on the basis of texture profiles which were measured according to a well-defined procedure using the LCPC stationary profilometer. For each road surface, 12 independent profiles are measured in the wheel tracks. They are evenly distributed on both sides of the pass-by noise measurement point and characterize a 12 m long section (6 profiles on each wheel track spaced out by 1 m). This procedure has been confirmed to provide a sufficiently small error in the texture level estimation.

An estimate of the error produced while evaluating the noise level from a finite texture length is provided in case of independent profiles. For an ordinary use, HyRoNE does not force the format and protocol regarding texture input data. Several (as well as one single) profiles can be set as input of the model. If several profiles are used for characterizing the same road surface, it is up to the user to make sure of the independency between these profiles.

3.2 Tyre characteristics

HyRoNE does not need any tyre data because it fits for one particular tyre. Other tyres are not provided for.

However, tyre data are quite important concerning the SPERoN model. The required macroscopic tyre parameters described in chapter 2.2 are derived from measurements of the tyre’s point mobility. Results of Shore hardness and inflation pressure measurements as well as 3D texture measurements of the tread profile complete the required data set.

3.3 Other parameters

SPERoN requires one more input parameter which is related to the road surface, the airflow resistance of the road surface texture. It is a proprietary quantity based on controlled measurements of the difference of the air pressure within a defined contact area and the atmospheric pressure at an airflow velocity of 0.0125 m/s. The contact area is realized by pressing an elastic ring on the road surface. A second additional parameter is the tyre load in kg.

For HyRoNE one more parameter which must be defined concerns the absorption properties of the road surface because HyRoNE is capable to be applied to this type of surfaces. The acoustical parameters used as input for HyRoNE are the porosity, the shape factor and the airflow resistance. The porous layer thickness is also required. Hamet's phenomenological model is used for evaluating the acoustical impedance of the porous medium [5][6].

Both models require the driving speed as input parameter. However, HyRoNE needs to be constructed for each rolling speed under consideration. Furthermore, the optimal envelopment parameter value fixed for one rolling speed is not necessarily the same as the one fixed for another speed. For the moment, HyRoNE provides pass-by noise predictions for three nominal speeds: 70 km/h, 90 km/h and 110 km/h. SPERoN takes any speed value between 30 km/h and 120 km/h without demanding a particular set of coefficients or exponents of the statistical model.

4 Output quantities and results

SPERoN's main output is the coast-by noise level spectrum in terms of 3rd octave band levels. The levels correpond to the spectrum which occurs when the maximum overall A-weighted sound pressure level is reached during the pass-by of a vehicle which is equipped with four tyres of the tyre under consideration. The levels correspond to 7.5 m distance and 1.2 m receiver height and are meant to be measured without engine noise (coast-by). Except for the total coast-by level spectrum the spectra of the four different noise components are output as well.

HyRoNE's main output is the pass-by global noise level in dB(A). The criterion used for fixing the value of the envelopment parameter E for the construction of HyRoNE is the error made between measured and predicted global levels averaged over the set of road surfaces used for the construction. The medium frequency range, where the highest third-octave levels occur, happens to be favoured with respect to the low and high frequency domains.

5 User access to the models

Users have access to an advanced version (V3.0) of the SPERoN model. It is realized as stand alone Windows application. In Fig.7 the SPERoN user interface is shown. To arrange a set of input data the user can choose one or more texture data files and one or more tyre data files. Thus, defining all tyre/road combinations which are calculated based on the speed and tyre load settings on the right hand side of the application window. By now, users can choose between 34 different types of tyres. Clicking the button *RunSPERoN* starts the calculation process for each tyre/road/speed combination which runs through the following steps:

1. Calculation of the tyre impulse response functions
2. Calculation of the tyre cavity excitation spectrum
3. Calculation of the non-linear contact stiffness functions
4. Calculation of the contact forces beginning with the tyre loading and running at least four loops
5. Evaluation of the multiple linear (regression) equation
6. Export of the results in XML file format and graphical presentation of the spectra

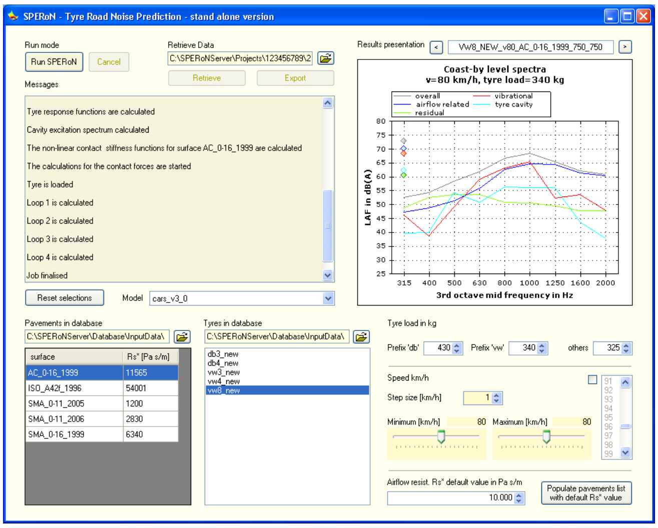

Fig.7 SPERoN user interface

In HyRoNE, the texture induced noise levels are directly evaluated from texture profiles. However, a certain flexibility is given to the user concerning the texture profile format, except for necessary requirements on length (sufficiently large) and sampling (sufficiently small) for enabling a noise evaluation. There is no need to provide tyre characteristics since the model is constructed for one specific tyre type.

The first version of HyRoNE is now implemented as a stand-alone application (Version 1.0). A view of the user interface is given in Fig.8. Only the texture part is addressed. Once the application has been launched, the user makes the selection of the texture profiles to be processed. The sampling and the height unit are to be defined. The selected profiles are preprocessed: the long wavelength components (above 1 m) and possible upward peaks are automatically removed from the raw profile. The preprocessing effect can be visualized on each selected profile. Once the preprocessing has been checked and the rolling speed is selected, the noise evaluation can be run. Practically, each preprocessed profile is subdivided into overlapping segments of equal length. These segments are enveloped, the enveloped and raw texture levels are estimated and the statistical laws are used to obtain the 3rd octave noise levels. In this way, one noise level is evaluated approximately every 0.5 m. Different results can be drawn: dB(A) global level as a function of position, averaged noise spectrum or 3rd octave levels as a function of position for each frequency between 100 Hz and 5 kHz. The software enables the evaluation of the homogeneity of a section by averaging (L_{eq} values) the noise levels over adjacent segments of a predefined length (20 m for instance). Finally, the results can be saved in Excel format files.

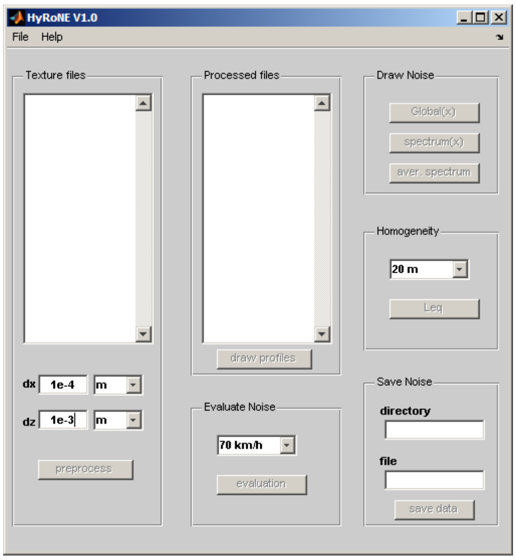

Fig.8 HyRoNE V1.0 user interface

6 Conclusions

The SPERoN and HyRoNE models are capable to calculate the pass-by noise levels of passenger car tyres depending on road surface characteristics and speed. Due to the statistical sub-models well defined datasets of a great deal of pass-by measurements with different tyre/road/speed combinations are needed in both cases in order to adjust the coefficients of the regression models with regard to least differences between calculation and measurement results.

However, the nonlinear problem of the tyre/road contact is dealt with in two explicitly different manners. In the HyRoNE model the dynamic system “tyre” is taken into account by determining an enveloped version of the road surface texture. The enveloped texture is obtained from the raw texture through an envelopment procedure applied to a texture profile. This procedure is based on a static contact model between the road profile and an elastic half space representing the tyre rubber. Spectral analysis of the enveloped texture profile and linear transformation from the wavelength into the frequency domain depending on speed provides a frequency spectrum as main input for the statistical model. In contrast to this static solution, the SPERoN model is based on the calculation of contact forces depending on time. The physical sub-module consists of two sub modules, the tyre model and the contact model. The tyre model is calculating the required impulse response functions which are used in the contact model.

Besides this, the SPERoN model requires a pre-processing of measured input data. This concerns the extraction of the main tyre data from measured point mobility and measured tread profile geometry and the preparation of the measured road surface textures for the contact module. In contrast to this, the HyRoNE model does not need any tyre data because the model and its parameters and coefficients fit to one particular type of tyre and speed combination. This is quite effective. However, every other tyre and speed combination would need to evaluate the HyRoNE model parameters anew based on a sufficient set of pass-by measurement data.

HyRoNE can process both impervious and porous, i.e. sound absorbing road pavements. The actual SPERoN version is restricted to dense road surfaces. The Dutch IPG (Innovation Program Noise) in 2006 and 2007 gave opportunity to further develop the model with respect to acoustic and mechanical impedance of road pavements and truck tyres [8]. It will be accessible by means of a web interface via internet as an extended version published by the SPERoN consortium (Chalmers (SE), Müller-BBM (D), M+P (NL)) in the near future.

Acknowledgements

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