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Prediction of pass-by levels depending on road surface parameters by means of a hybrid model

Thomas Beckenbauer*, Ard Kuijpers**
* Müller-BBM GmbH, Germany, www.mbbm.de, bec@mbbm.de
** M+P noise and vibration consultants, The Netherlands, www.mp.nl, kuijpers@db.mp.nl

Abstract

Based on research work for the German Highway Research Institute (the "Sperenberg project"), the combination of a statistical and a physical model (hybrid model) for the prediction of coast-by levels of car tyres depending on road surface parameters, the so-called SPERoN model, has been developed. Physical preprocessing is used to condition the non-acoustic input quantities. Clapp´s algorithm is applied to calculate the contact pressure distribution within the tyre-road contact patch depending on the texture profile of the road surface. The shape factor g helps to improve the discrimination between convex and concave textures. These new parameters are suitable to serve as linearly dependent variables for a statistical regression model which cares for the quantification of the approach. 80% of the variance of coast-by levels can be explained by the contact pressure spectrum, the shape factor, the tyre width and the rolling speed. At frequencies above 1 kHz a remarkable influence of mechanical noise generation mechanisms has been detected.

1. Introduction

This paper describes the first approach for a computational model which allows the prediction of coast-by levels by using road surface parameters as input quantities. The coast-by level is defined as maximum A-weighted sound pressure level L_{pAF} during the coast-by of a vehicle at a distance of 7.5 m to the centre of the vehicle. The height of the receiver point is 1.2 m above ground. At present the model is restricted to dense road surfaces with isotropic textures. The predicted coast-by levels fit to a collective of normal passenger car tyres customary in trade. The development of tyre road noise models generally runs into two major problems:

- the complexity of the system with all the different noise generation mechanisms
- an incomplete set of input parameters which are insufficient in many cases to be able to predict the acoustical target quantity with the necessary precision

In order to reduce complexity and the necessity for large input parameter sets a hybrid model has been pursued. The term hybrid model stands for the combination of physical preprocessing and a statistical model. The physical preprocessing is used to condition and to transform the (measured) non-acoustic input quantities in such a way that a statistical regression model can be fed with input variables which are linearly connected with the target quantity i.e. the coast-by level and its third-octave-band spectrum. The statistical part of the hybrid model cares for suitable quantitative coupling of the input variables and the coast-by level at the output thru adjustment of the regression coefficients.

The contact pressure distribution within the tyre-road contact patch plays an important role [1] [2] [3]. However, there is a non-linear dependence of the contact pressure on the roughness profile of the road surface. For this reason, the direct linear correlation of road texture quantities with the acoustical target quantity is inadequate. Therefore, the only input variable for the statistical model may be the contact pressure distribution or the contact pressure spectrum. In addition to the contact pressure, other non-acoustic variables may be needed to obtain sufficient accuracy of results.

2. Description of the model

2.1 Stepwise modelling

The statistical model was developed step-by-step. Each step included the addition of one more input variable extending the model by a new physical parameter. With every new set of variables and coefficients, a multivariate regression analysis was carried out. The results had to be evaluated by testing the following requirements:

- the variables are independent, hence generating normally distributed residuals
- with each new variable the coefficient of determination r^2 must get higher, hence improving the variance explained by the model in relation to the total variance
- the influence of the variables on the spectrum of the coast-by level makes sense in physical terms, hence being compatible with findings known from literature.

Finally the statistical model got the following form:

$$L_{pAF,i} \sim c_{vAF,i} \cdot 10 \lg\left(\frac{v}{v_0}\right) dB + c_{cAF,i} \cdot L_{cF,i} + c_{wAF,i} \cdot w + c_{gAF,i} \cdot L_g \quad (1)$$

where $L_{pAF,i}$: A-weighted sound pressure level in the i-th third octave band in dB
$c_{vAF,i}$: regression coefficient for the speed term
v : rolling speed in km/h
v_0 : reference rolling speed, here: $v_0 = 80$ km/h
$c_{cAF,i}$: regression coefficient for the third-octave-band level of the contact pressure
$L_{cF,i}$: level of the frequency transformed contact pressure for the i-th third-octave band in dB
$c_{wAF,i}$: regression coefficient for the tyre width
w : tyre width in mm
$c_{gAF,i}$: regression coefficient for the shape level
L_g : shape level in dB

The evaluation of the regression coefficient $c_{vAF,i}$ is of major interest. This coefficient can be interpreted as speed exponent and its value characterizes the type of sound source behind the noise generation mechanism which is effective in the frequency range concerned [1].

Figure 1 shows the scheme of this first approach for the hybrid model SPERoN (Statistical Physical Explanation of Rolling Noise). The left side shows the set of (measured) input quantities the model is fed with. At the output of the preprocessing unit there are two quantities which are derived from the input quantities: the shape factor *g* and the contact pressure spectrum $L_c(f)$. Both are explained in the following paragraphs. The statistical model has the form specified in equation (1).

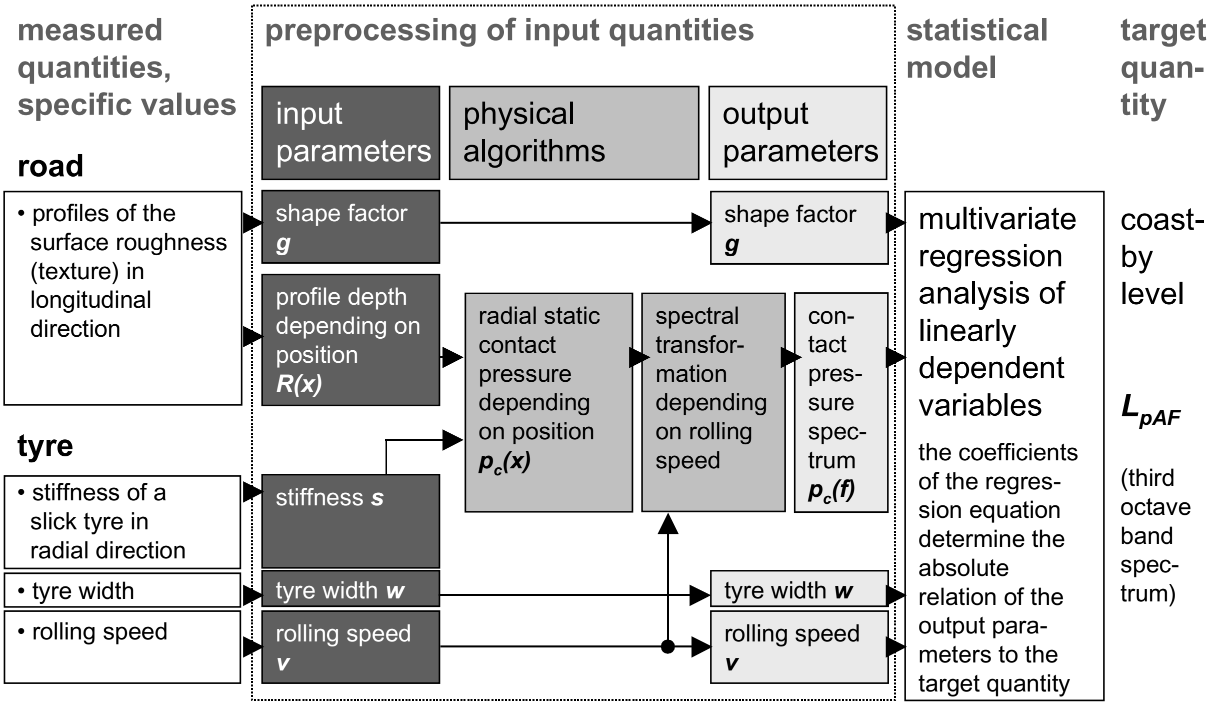

Figure 1: Scheme of the first approach for the hybrid tyre road noise model SPERoN.

2.2 Shape factor *g*

Hamet and Klein [4] correctly concluded that two road surfaces with identical texture amplitude spectra do not necessarily show identical acoustical behaviour. Taking both the amplitude and the phase information of the texture profile into account is likely to be a better solution. However, the shape factor introduced here is another approach. It is derived from the Abbot curve of a profile as shown in figure 2 for both convex and concave shaped textures. The curve indicates the percentage contact length *PCL* within the characteristic profile length of 100 mm depending on penetration. The shape factor *g* corresponds to the *PCL* value at 50% penetration. Convex and concave shapes can be clearly discriminated.

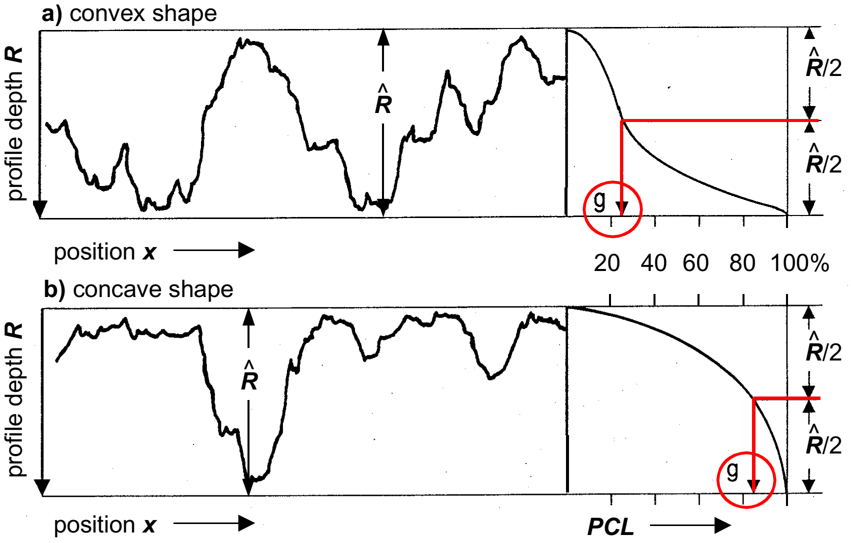

Figure 2: Definition of the shape factor *g*. The straight line on the right represents the Abbot curve which is derived from the roughness profile on the left. The shape factor corresponds to the percentage contact length *PCL* at 50% penetration as indicated ($R = \hat{R}/2$); a) asphalt with surface dressing , b) hot rolled asphalt.

In the first case *g* takes values between 20% and 50%, in the second case the value is 60% up to 90%. The shape level L_g is used as variable for the statistical model:

$$L_g = 20\ \lg\left(g / 1\%\right)\ dB \tag{2}$$

2.3 Contact model

The contact pressure distribution within the tyre-road contact patch is calculated by means of the algorithm by Clapp et al. [5]. The algorithm applies to the static case, assuming a contact patch of 100 mm in length. As input quantities, the non-linear algorithm uses both the road surface profile and an average radial stiffness *s* of the tyre tread. It yields the contact pressure $p_c(x)$ as a function of the position *x* in longitudinal direction. The frequencies of the spectral components caused by mechanical noise generation depends on the frequency of tread-road surface contacts per time unit. Therefore, it depends on rolling speed *v*. This is taken into account by using the following position-to-time transformation:

$$p_c(t) = p_c(x/v) \tag{3}$$

The Fourier transformation of $p_c(t)$ yields the spectrum of the contact pressure. The contact pressure level $L_{cF}(f)$ is defined as follows:

$$L_{cF}(f) = 20\ \lg\left(\frac{p_c(f)}{p_{c0}}\right) dB \tag{4}$$

where $p_{c0} = 10^{-6}$ N/m^2. Figure 3 shows the contact pressure spectra for two different road surfaces depending on speed. Increasing speed leads to a considerable decrease of spectral energy within the frequency range from 800 Hz to 1250 Hz, especially for the rough surface (b).

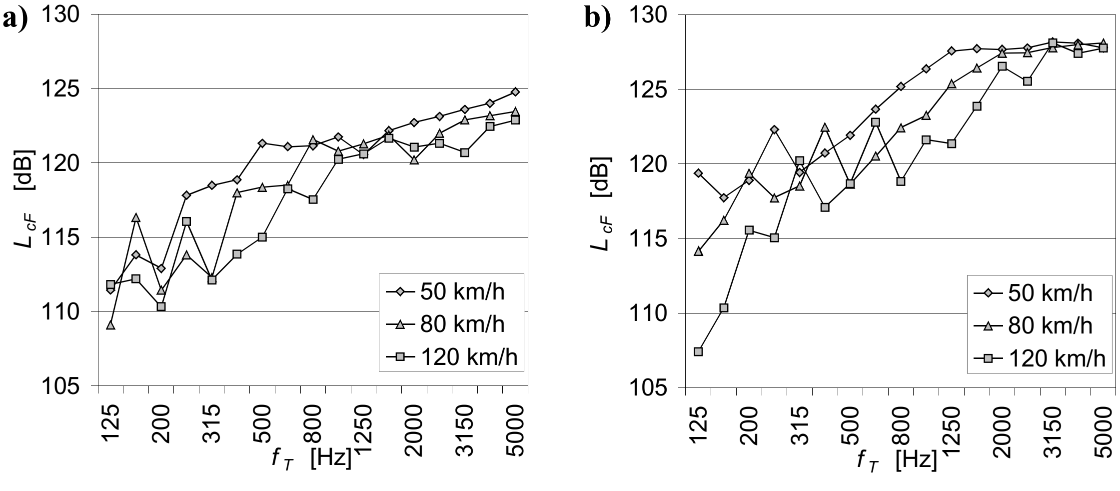

Figure 3: Result of the spectral transformation of the contact pressure level L_{cF} for two different road surfaces at three different rolling speeds *v*; a) stone mastic asphalt 0/8, b) surface dressing 3/5.

3. Input data

The calculation of the regression coefficients results in quantification of the coast-by levels related to the input quantities. This procedure needs a large and well documented data set which is available in terms of measuring results gained within the scope of the German research project “Influence of the road surface texture on the tyre-road noise” (also known as “Sperenberg project”) [6]. The database consists of texture data and coast-by level spectra for 840 different tyre road combinations at rolling speeds from 50 km/h up to 120 km/h, including 21 dense road surfaces, 12 normal, 2 slick and 2 groove passenger car tyres. Due to thoroughly adjusted and controlled boundary conditions the model can be fed with data free from disturbing influences caused by different temperatures, varying tyre inflation pressures etc..

4. Results

Figure 4 shows the coefficient of determination r^2, the regression coefficients for the shape level c_{gAF} and the speed term c_{vAF} depending on frequency. The results are shown for three different kinds of tyres. Due to r^2 values of approximately 0.9 the reliability of the model for slick tyres is remarkably high. Even normal tyres lead to satisfying values above 0.7. The introduction of shape level L_g improves the reliability by 4% points comparing the r^2 values for the results with (straigth line) and without the variable L_g (dashed line in figure 6a). Moreover, the spectrum for the contact pressure coefficient c_{cAF} does not alter when L_g is introduced. This indicates that the shape factor is an independent variable and does introduce new information. The shape level influences the coast-by levels in a wide frequency range.

Aerodynamic noise caused by the air pumping effect has long been held responsible for noise generation at high frequencies. The sound sources involved lead to speed exponents of ≥ 4.0 [1]. As can be seen in the frequency response of the speed coefficient c_{vAF}, this is valid only for slick tyres. The coefficients for normal tyres fall distinctly below this value. This implies that mechanical noise generation mechanisms take effect as well. At medium frequencies, the c_{vAF} value corresponds to the speed exponent for radial vibrations of the tyre [1].

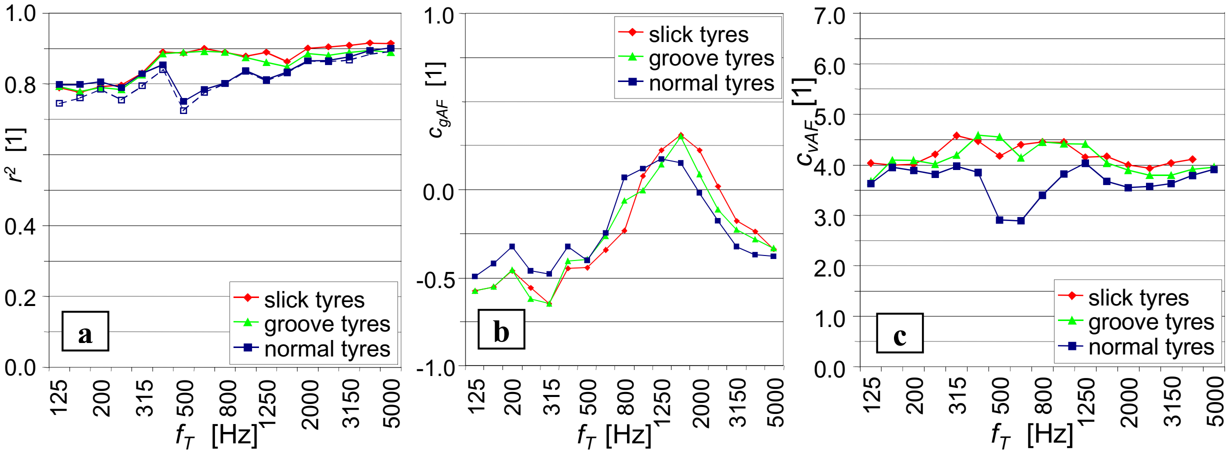

Figure 4: a) Coefficient of determination r^2, b) regression coefficient for the shape level c_{gAF} and c) regression coefficient for the speed term c_{vAF} depending on third-octave centre frequency f_T. Parameter: kind of tyre. The dashed line in a) is valid for the statistical model without the variable L_g (shape level).

Figure 6 shows the results of a parameter variation carried out by means of the hybrid model. The results are valid for $g < 60\%$ and $v = 80$ km/h. Two parameters are varied: λ_{max} and R_{max}. Texture spectra of real road surfaces with low g values show distinctive spectral maxima. Based on a typical texture spectrum the definition of λ_{max} and R_{max} is explained in figure 5. Both parameters were varied independently. Shape factor and quality of the spectral envelope remained unchanged. The black rectangle in figure 6 denotes the range of texture parameters which turned out to be optimal for noise reducing road surfaces due to the results of the measurements carried out with 21 dense surfaces of the Sperenberg project [6]. The results of the model show that there must be a lot of textures that might lead to still lower coast-by levels. But this can only be proved if such textures can be effectively laid down.

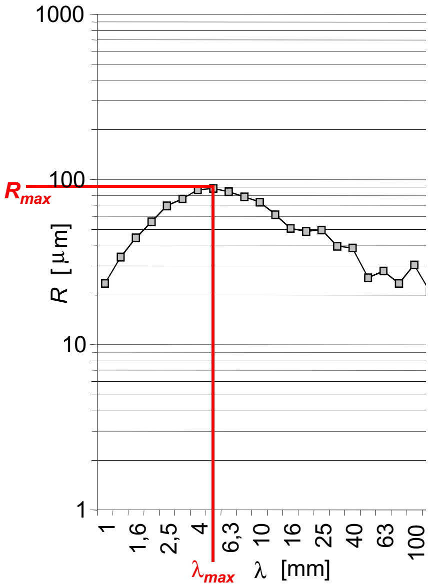

Figure 5: Definition of the roughness depth R_{max} and the wave length λ_{max} based on a real texture spectrum.

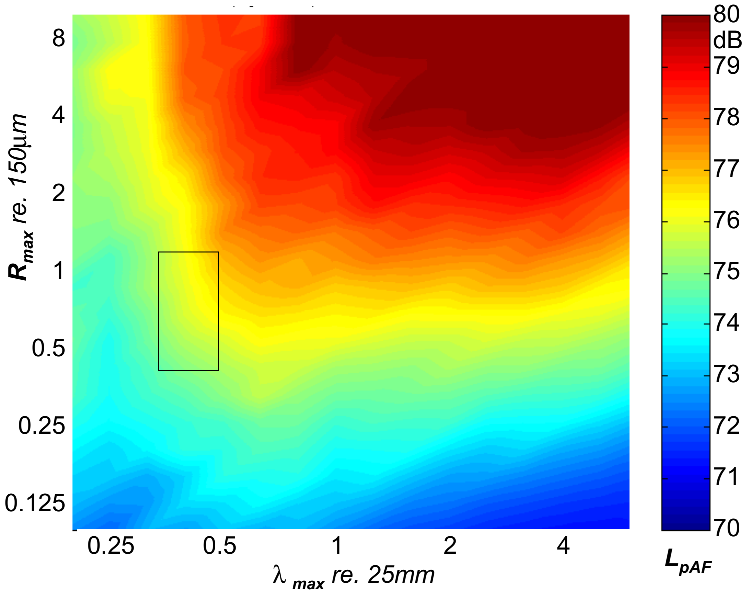

Figure 6: Calculated coast-by levels L_{pAF} for $v = 80$ km/h and $g < 60\%$ depending on roughness depth R_{max} and wavelength λ_{max} of the spectral maximum. Rectangle: see text.

Conclusions

80% of the variance can be explained just by four parameters: speed, frequency transformed contact pressure spectrum, tyre width and shape factor. There are 20% variance left that may be explained by the strong influence of tyre tread blocks (compare r^2 for normal tyres with r^2 for slicks at medium frequencies!) not yet taken into account, and further non-linear dependences of the tyre road noise. It seems that there might be a remarkable influence of tangential forces in the high frequency range. Missing parameters like mechanical impedance, acoustic impedance and air flow resistance could help to improve the model.

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