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PREDICTION OF COAST-BY TYRE/ROAD NOISE LEVELS AT PERI-URBAN AND URBAN SPEEDS

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ABSTRACT

The paper deals with the prediction from texture related quantities of Coast-By (CB) tyre/road noise levels emitted by a passenger car at peri-urban and urban speeds, using a hybrid model that mixes simplified physical models and statistical relationships. One-third octave band noise levels are predicted from one-third octave band roughness levels. A 3D “enveloped” roughness that combines road texture and tyre tread pattern is used to evaluate the noise levels in the low and medium frequency range. The road texture at small wavelengths is used to predict the noise levels in the high frequency range. The model is built at several reference speeds by adjusting the statistical relationships coefficients between noise and roughness levels upon a database of 12 impervious road surfaces with quasi-smooth to coarse textures. The predicted one-third octave band and overall CB noise levels are compared to the measured noise levels. The results are discussed, in particular with regard to the reference speed considered.

1. INTRODUCTION

This paper deals with the prediction of Coast-By tyre/road noise levels emitted by a passenger car on impervious road surfaces. The noise levels are predicted from road surface texture which is acknowledged to play a significant role in rolling noise generation [1] and from the tread pattern of the tyres fitted to the test vehicle that may also influence the rolling noise especially for rather smooth road surfaces.

The model uses a hybrid approach that combines a physical contact model and statistical relationships calibrated with experimental data [2-3]. Input data are 3D road surface texture and tyre tread pattern combined for providing tyre/road roughness quantities. The model was previously constructed for predicting noise levels at peri-urban speed (90 km/h) [4]. Here it is constructed to predict noise levels also at urban speed. The experimental database comprises 12 impervious road surfaces with quasi-smooth to very rough textures.

The road surface database used for the model calibration is presented in part 2. Texture and noise spectra are presented in part 3 together with the associated correlations providing noise prediction formula in the high frequency range. Part 4 is dedicated to the presentation of the 3D envelopment procedure that provides texture related quantities used to predict tyre radiated noise levels in the low and medium frequency range. The correlations with noise obtained for several reference speeds are also

presented. The model is described in part 5 and the calibration results are given regarding one-third octave and overall noise levels prediction.

2. ROAD SURFACE DATABASE

The prediction model is built on a set of road surfaces. The road surface database includes noise and texture measurements performed on 12 road surfaces of Université Gustave Eiffel reference test track located in Bouguenais (France).

2.1 Tyre/Road Noise Measurements

Close-Proximity (CPX) and Coast-By (CB) measurements have been performed simultaneously to characterize tyre/road noise over 20 meters of each road surface [5]. Several runs were performed for different nominal speeds ranging from 30 km/h to 110 km/h with a 5 km/h interval. To avoid engine noise, the transmission of the test vehicle was put in neutral gear just before entering the 20 m section. At the lowest speeds, the engine was switched off. For each run, the average actual speed was retrieved from the CPX measurement system.

The test vehicle was a Renault Scenic fitted with patterned Michelin Energy E3A 195/60R15 tyres (see Fig. 1).



Figure 1. Test vehicle and tyre.

For each surface, the measured noise levels are regressed as a function of the logarithm of the rolling speed over the whole speed range to obtain overall and one-third octave band noise levels at different reference speeds 50, 70 and 90 km/h.

2.2 3D Texture Measurements

Texture measurements have been performed with a 3D texture measurement system (See Fig. 2). This system, which includes a laser profile sensor, provides longitudinal strips readings that allow the reconstruction of 35 cm wide and 1.50 m long texture samples with 0.1 mm resolution.



Figure 2. 3D texture measurement system.

For each pavement, two to four such texture samples were measured in the CPX measurement wheel path and centered on the CB measurement microphone position.

2.3 Road Surfaces

The road surfaces considered in this paper are impervious (non porous) surfaces. Three of these surfaces are or can be considered smooth (ISO, C1), including a slick epoxy resin (L1). Two are very rough surfaces (A', C2). The others present intermediate texture. All are listed in Tab.1 sorted by increasing Mean Profile Depth.

| Name | Type | Grain size [mm] | MPD [mm] |
|------|---------------------------------------|-----------------|----------|
| L1 | Epoxy Resin | - | 0.05 |
| ISO | Dense Asphalt Concrete (ISO 10844) | 0/8 | 0.31 |
| C1 | planed (grind) Dense Asphalt Concrete | 0/10 | 0.33 |
| L2 | Sand Asphalt | 0/4 | 0.73 |
| G0 | Flexible Dense Asphalt Concrete | 0/10 | 0.74 |
| E1 | Dense Asphalt Concrete | 0/10 | 0.83 |
| E3 | Stone Mastic Asphalt | 0/10 | 0.91 |
| E2 | Dense Asphalt Concrete | 0/10 | 0.98 |
| F | Surface Dressing | 1.5/3 | 1.40 |
| M1 | Very Thin Asphalt Concrete (type 1) | 0/2-6/10 | 1.50 |
| A' | Surface Dressing | 8/10 | 3.28 |
| C2 | Surface Dressing | 0/14 | 3.98 |

Table 1. Road surfaces considered.

3. TEXTURE AND NOISE SPECTRA

3.1 Raw Texture Levels

The one-third octave band raw texture levels are evaluated from 1.5 m long longitudinal profiles extracted from the measured surfaces. They are drawn in Fig. 3 for

wavelengths ranging between 2 mm and 500 mm. The markers corresponding to each surface are indicated in this graph and will not be repeated in other graphs.

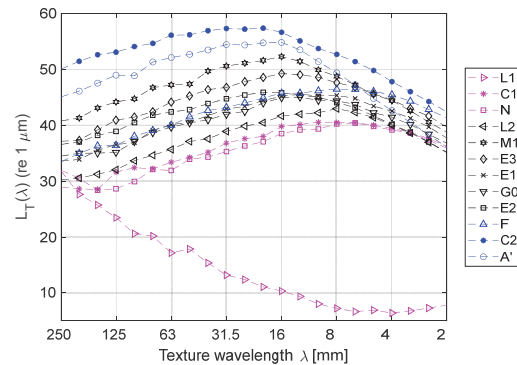


Figure 3. Raw texture levels.

3.2 Noise Levels

The acoustical assessment of road surfaces is detailed in [5]. The one-third octave band noise levels are drawn in Fig. 4 for two reference speeds 50 and 90 km/h. It should be remembered that these are levels obtained by logarithmic regression as a function of speed. This leads to the smoothing of peaks at tyre pitch frequency especially for smooth surfaces at low speed. This is particularly the case for surfaces L1 and C1 at 50 km/h for which the 500-630 Hz peak completely disappears whereas it is very pronounced on non-regressed spectra. This is also partly true at 90 km/h for the 1kHz peak. The latter are plotted in Fig. 5 for test speeds closest to 50 km/h and 90 km/h for information.

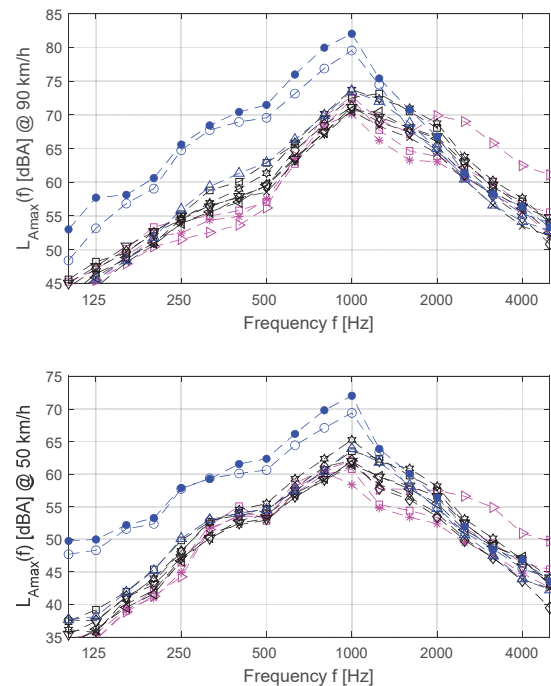


Figure 4. CB noise spectra for reference rolling speeds. Top: 90 km/h – Bottom: 50 km/h.

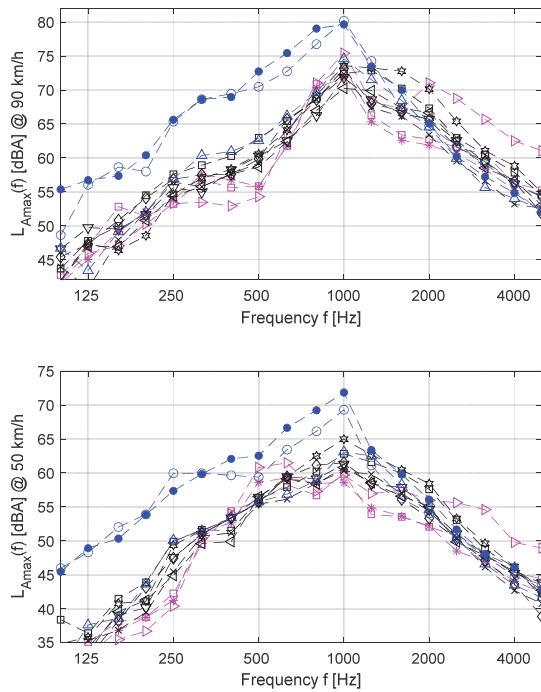


Figure 5. Non-regressed measured CB noise spectra for rolling speeds closest to 90 km/h (top) and 50 km/h (bottom).

3.3 Correlation between Raw Texture Levels and Noise Levels

As preliminary results, following the approach suggested in [1], the correlation coefficients between one-third octave band noise levels and one-third octave band texture levels are calculated for wavelength/frequency pairs (λ_i, f_j) . The corresponding maps are represented in Fig. 6 for the reference speeds 50 km/h and 90 km/h.

The same trends as those given in [1] are observed: positive correlations between noise levels in the low and medium frequency range and large wavelength (above 63 mm) texture levels on the one hand, negative correlations between noise levels in the high frequency range and texture levels at small wavelengths on the other hand. At intermediate (transition) frequencies (1250, 1600 and 2000 Hz) poor correlations are observed.

4. 3D ENVELOPMENT OF COMBINED ROAD/TYRE ROUGHNESS

4.1 Principle

The envelopment procedure is intended to provide the upper part of the road texture likely to enter into contact with the tyre tread, thus to improve the texture/noise correlations in the low and medium frequency range where the noise generation is attributed to the tyre carcass vibration induced by normal contact forces. The 3D envelopment procedure is described in [4]. It is based on an elastic 3D contact model similar in essence to that described in [6]. It consists in evaluating the deformation

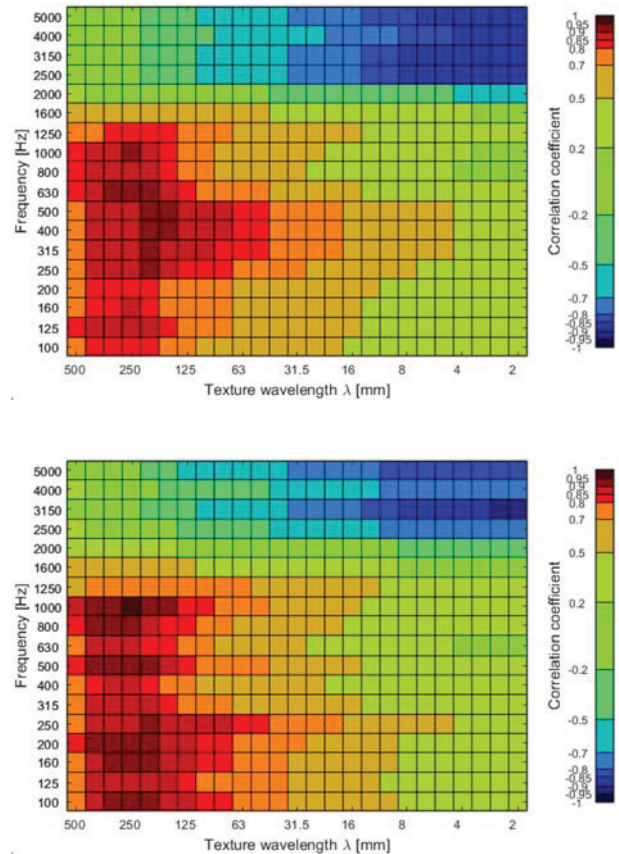


Figure 6. Correlation coefficient maps between raw texture levels and noise levels for reference speeds – Top: 90 km/h – Bottom: 50 km/h.

of an elastic plane block which is progressively moved over the roughness to be characterized. The problem is made periodic in the longitudinal direction for avoiding edge effects at the block edges. The resulting “enveloped” surface consists of the juxtaposition of the central transverse deformed profile of the sliding block (shown in red in Fig. 7). A pressure map is obtained in exactly the same way by juxtaposition of the contact pressure evaluated along the central profile.

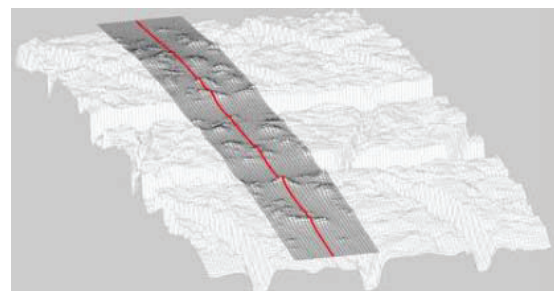


Figure 7. Loaded elastic block (in black) moved over the combined tyre/road roughness.

To account for both tyre and road roughness a combined roughness is obtained by adding the tyre tread height to the texture height. This is illustrated in Fig. 8 for profiles transverse to the rolling direction. The sampling interval in

both transverse and longitudinal (rolling) direction is 1 mm.

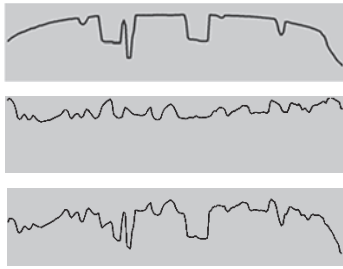


Figure 8. Top: tyre tread profile – Middle: road texture profile – Bottom: combined tyre/road profile.

Examples of enveloped surfaces (21 cm wide and 30 cm long) and associated pressure maps are shown in Fig. 9 for road surfaces ISO (quasi-smooth) and A' (very rough).

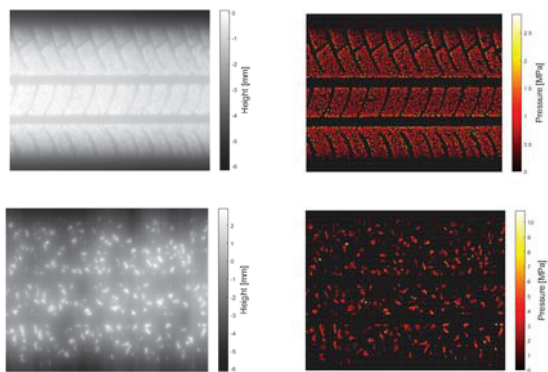


Figure 9. Left: enveloped surfaces - Right: contact pressure maps - Top: surface ISO - Bottom: surface A'.

4.2 3D Envelopment Output

The envelopment procedure for predicting noise levels in the low and medium frequency range are chosen to be enveloped combined roughness levels L_{eT} in the rolling direction averaged over several extracted profiles as described in [4]. These levels do not take into account the phase information between longitudinal profiles. Another quantity has been tested that consists in averaging complex spectra in the transverse direction over the whole contact width as proposed in [7] to obtain coherent profile spectra L_{eCT} taking into account lateral coherence between enveloped longitudinal profiles. Both types of spectra are drawn in Fig. 10. The peaks at 25 mm and 12.5 mm observed for quasi-smooth surfaces correspond to tyre tread pitch fundamental and first harmonic. One can also notice the drop in rough surface coherent spectra at 25 mm and 10 mm unlike incoherent spectra.

To be consistent with noise regression analysis with respect to rolling speed, the enveloped roughness spectra as a function of frequency V/λ are also logarithmically regressed among all noise measurement speeds to obtain frequency dependent enveloped tyre/road roughness

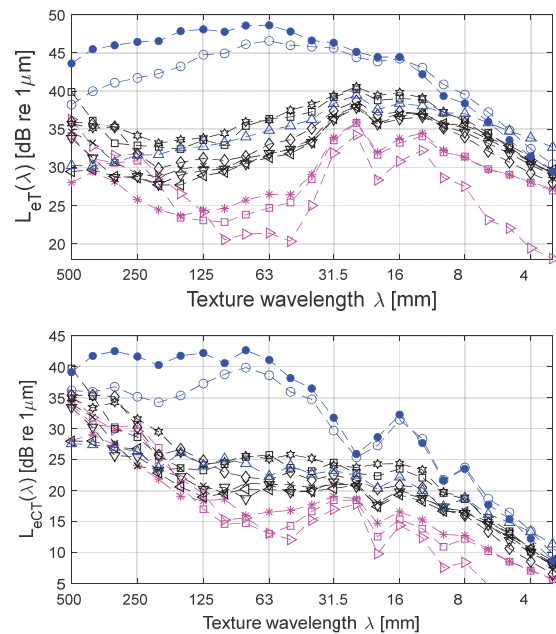


Figure 10. Top: enveloped combined tyre/road roughness spectra – Bottom: mean transverse pressure spectra.

spectra for the reference speeds considered. These are plotted in Fig. 11 for 50 and 90 km/h. For $V=90$ km/h, the peaks at 1 kHz and 2 kHz for quasi-smooth surfaces correspond to those at 25 mm and 12.5 mm in Fig. 10. They are less pronounced but still visible. For lower speed the peaks are smoothed. At 50 km/h, the peak corresponding to 25 mm that should occur at 550 Hz is completely smoothed in a similar way to noise spectra. The regressed coherent enveloped roughness spectra are drawn Fig. 12. Similar trends can be noticed.

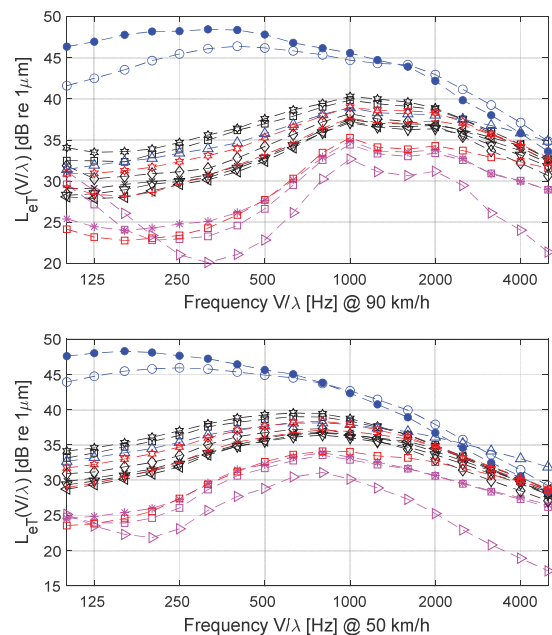


Figure 11. Regressed enveloped tyre/road roughness spectra for two reference speeds – Top: 90 km/h – Bottom: 50 km/h.

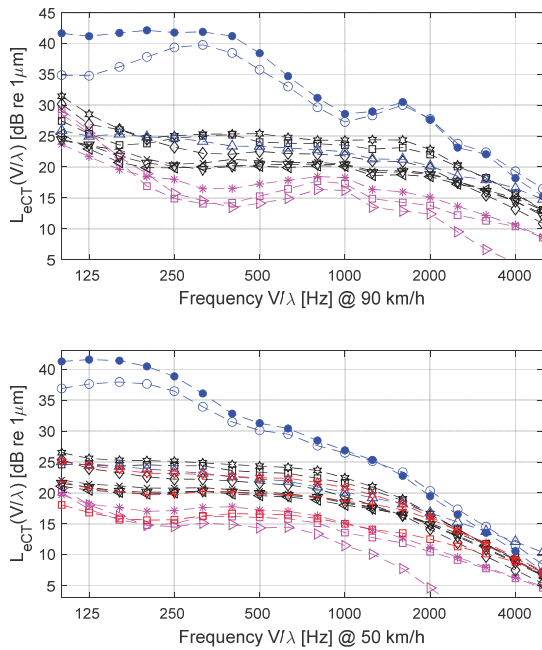


Figure 12. Regressed coherent envelopment roughness spectra for two reference speeds – Top: 90 km/h - Bottom: 50 km/h.

4.3 Correlations between Enveloped Roughness Levels and Noise Levels

The correlation coefficient between one-third octave band noise levels and enveloped combined roughness levels are evaluated for frequency pairs $(V/\lambda_i, f_j)$ and drawn Fig. 13 for the rolling speeds 50 and 90 km/h. These correlation maps show higher correlation coefficient values in the low and medium frequency range with respect to those obtained for raw texture levels. However, at certain frequencies the correlation coefficient does not exceed 0.8. This is the case particularly for the lowest speed ($V=50$ km/h) at 400 Hz and 630 Hz.

The correlation coefficient obtained with the coherent enveloped roughness levels L_{eCT} are drawn Fig. 14. The correlations are slightly improved with respect to those obtained with incoherent roughness levels L_{eT} . Again, in this case, correlations at 400 Hz and 630 Hz are not so good than for other frequencies in the low and medium frequency range.

The noise levels at 50 km/h and 90 km/h are plotted against the coherent enveloped roughness levels in the one-third octave band 630 Hz in Fig. 15 as illustration. The regression line is plotted in black. As can be observed, for $V=90$ km/h, the points are quite close to the regression line even if a slight curved trend can be seen with highest deviations for the quasi-smooth and very rough surfaces. For $V=50$ km/h, this curved trend is amplified which explains poorer correlation. A very similar trend can be observed with incoherent enveloped roughness levels. This means that even when introducing tyre tread pattern, a linear relationship between roughness and noise is not obtained with smooth surfaces especially at low speeds.

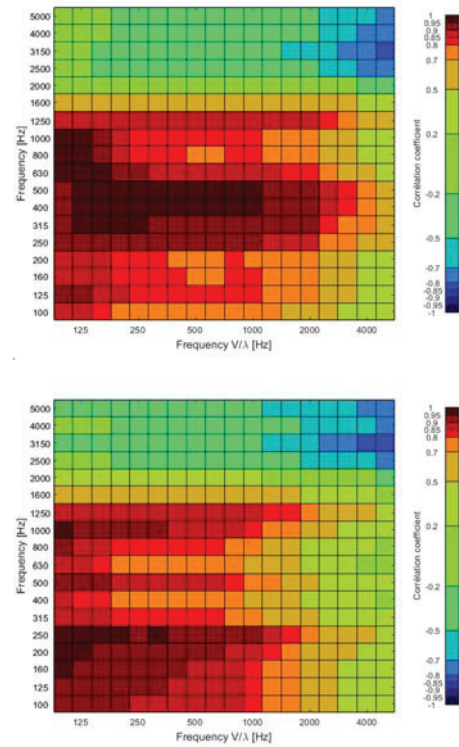


Figure 13. Correlation coefficient maps between enveloped combined roughness levels and noise levels for reference speeds – Top: 90 km/h – Bottom: 50 km/h.

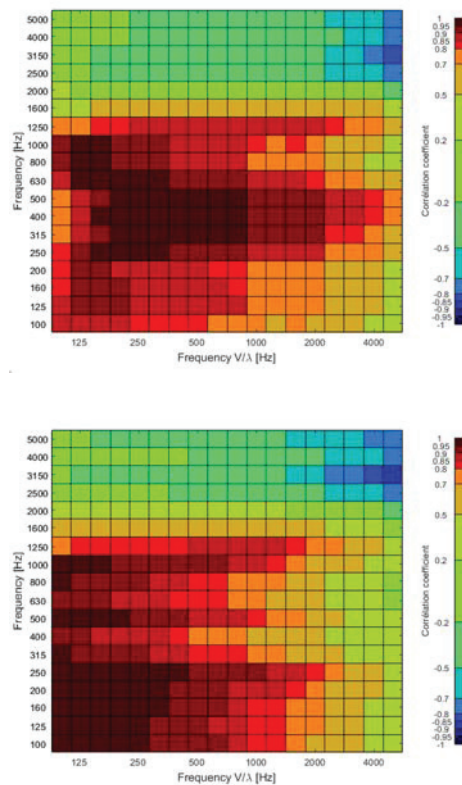


Figure 14. Correlation coefficient maps between coherent enveloped roughness levels and noise levels for reference speeds – Top: 90 km/h – Bottom: 50 km/h.

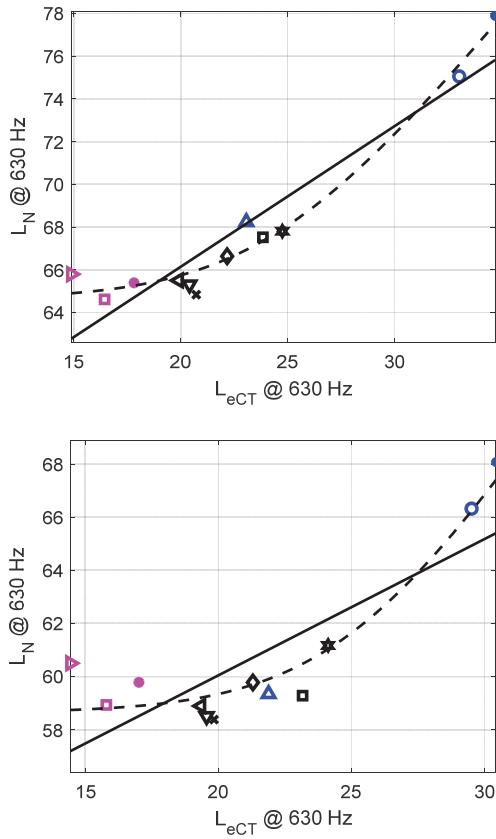


Figure 15. Noise levels versus coherent enveloped roughness levels in one-third octave band 630 Hz - Top: at 90 km/h – Bottom: at 50 km/h.

5. PREDICTION MODEL

5.1 Principle

Based on the correlation analysis presented above, the prediction model distinguishes two frequency domains: the low and medium frequency range where tyre/road noise is mainly attributed to the radiation of the tyre belt, and the high frequency domain where rolling noise is mainly attributed to air-pumping. The transition frequency f_t is the limit between both domains. One-third octave noise levels from 100 Hz to 5 kHz are predicted from enveloped roughness levels or raw texture levels.

In the low and medium frequency range, the noise level at frequency f_i is predicted from regressed one-third octave (incoherent or coherent) enveloped roughness level at wavelength $\lambda_i = V / f_i$, where V is the rolling speed.

The prediction formula is an energetic combination of a linear roughness-related component and a constant component introduced to address the non linear behaviour of quasi-smooth surfaces mentioned previously:

$$L_N(f_i) = 10 \log(10^{L_0(f_i)/10} + 10^{(a(f_i)+b(f_i).L_{eT}(V/f_i))/10}) \quad (1)$$

where $a(f_i)$, $b(f_i)$ and $L_0(f_i)$ are determined for $f_i \leq f_t$ by minimizing the quadratic error between measured

and predicted noise levels. Examples of fitted relationship at 630 Hz are drawn as a dashed lines in Fig. 15 for coherent roughness levels L_{eCT} .

In the high frequency range ($f_i > f_t$), the one-third octave band noise levels are predicted from octave band raw texture level at wavelength λ_0 :

$$L_N(f_i) = a(f_i) + b(f_i).L_T(\lambda_0) \quad (2)$$

where $a(f_i)$ and $b(f_i)$ are determined for $f_i > f_t$ by linear regression.

The coefficients of statistical relationships are determined for each reference rolling speed. Regarding the different correlation maps previously obtained, the transition frequency f_t and the wavelength λ_0 have been chosen to be respectively 1600 Hz and 2.5 mm for all reference speeds.

5.2 Prediction Error on One-Third Octave Band Noise Levels

The errors on one-third octave noise prediction obtained with incoherent and coherent enveloped roughness levels are drawn in Fig. 16 and Fig. 17 as a function of frequency for the reference speeds 50, 70 and 90 km/h.

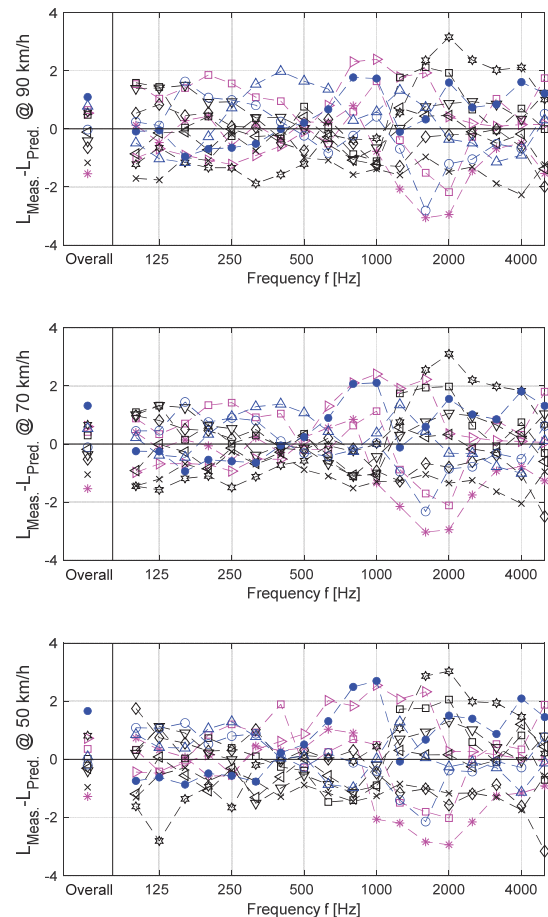


Figure 16. One-third octave band prediction errors obtained with incoherent enveloped roughness levels for reference speeds 50, 70 and 90 km/h.

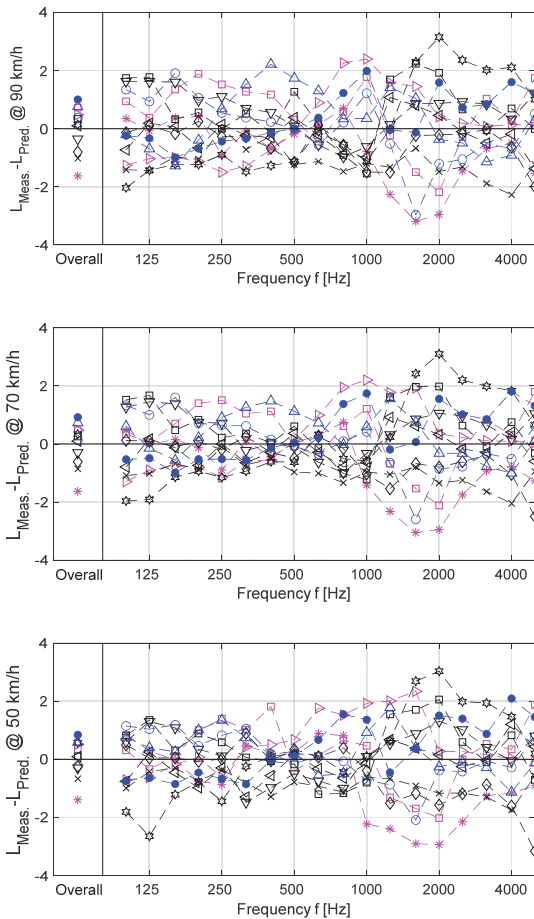


Figure 17. One-third octave band prediction errors obtained with coherent enveloped roughness levels for reference speeds 50, 70 and 90 km/h.

The results in terms of mean prediction error (root mean square values) are synthesized in Fig. 18. The errors are rather small below 800 Hz due to the use of a prediction law with two components. Between 800 Hz and 2 kHz, where air-pumping and tyre belt radiation are supposed to contribute together to noise generation [1], they reach higher values. Above 2 kHz they are rather small, slightly higher than those below 800 Hz.

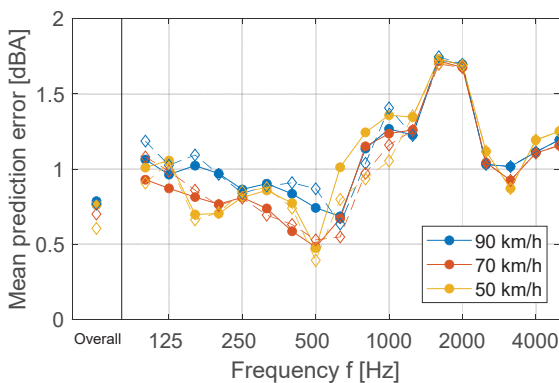


Figure 18. One-third octave band mean prediction errors obtained with incoherent (continuous lines) and coherent (dashed lines) enveloped roughness levels for reference speeds 50, 70 and 90 km/h.

In light of these results, there is no particular trend that would demonstrate a better effectiveness of one enveloped roughness quantity with respect to the other for noise prediction in the low and medium frequency range. However, at 50km/h the coherent levels lead to smaller mean prediction error between 630Hz and 1000 Hz.

5.3 Prediction Error on Overall dBA Noise Levels

Overall dBA noise levels are recomposed from one-third octave noise levels for frequencies ranging between 100 Hz and 5 kHz according to the expression:

$$L_{Amax} = 10 \log(\sum_i 10^{L_N(f_i)/10}) \quad (3)$$

The correspondence between measured and predicted overall noise levels is given for the reference rolling speeds 50 km/h and 90 km/h in Fig. 19 for predicted levels in the low and medium frequency range obtained from incoherent roughness levels and in Fig. 20 for those obtained from coherent roughness levels. Good correspondence is obtained with a highest prediction error among all road surfaces lower than 2 dBA. For the model based on incoherent spectrum the mean prediction errors for reference speeds 50, 70 and 90 km/h amount to 0.8 dBA. For the model based on coherent spectrum, they amount respectively to 0.6, 0.7 and 0.8 dBA.

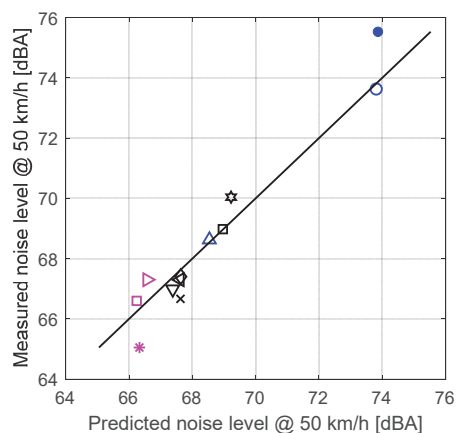
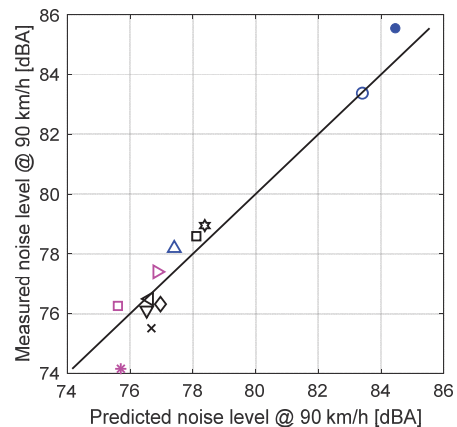


Figure 19. Correspondence between predicted and measured overall dBA noise levels for reference speeds 50 and 90 km/h (prediction from incoherent roughness levels in the low and medium frequency range).

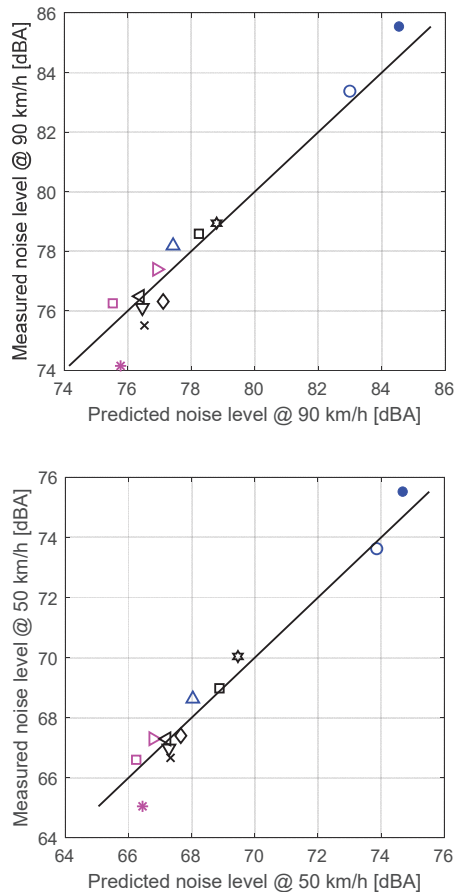


Figure 20. Correspondence between predicted and measured overall dBA noise levels for reference speeds 50 and 90 km/h (prediction from coherent roughness levels in the low and medium frequency range).

6. CONCLUSION

In this study, a hybrid model has been constructed for the prediction from 3D texture samples of Coast-By tyre/road noise levels of a passenger car at reference rolling speeds ranging between 50 km/h and 90 km/h. The noise levels are predicted from enveloped combined tyre/road roughness levels in the low and medium frequency range, and from raw texture levels at small wavelengths in the high frequency domain.

Two types of enveloped roughness levels have been tested. The first one is obtained by amplitude averaging over the contact zone width while the second is obtained by amplitude and phase averaging to account for lateral coherence of the tyre excitation. In both cases, the errors made on one-third octave band noise level prediction are similar, quite small below 800 Hz, larger between 1000 Hz and 1600 Hz. However, it should be noted that the calculation of the coherent spectrum is based in a fairly simple way i.e. transverse to the rolling direction and over the entire width of the contact zone. It would probably be possible to refine its evaluation by subdividing the width of the contact zone into several sections and by adapting the alignment of adjacent profiles to the actual shape of the

contact zone which determines the set of tyre elements impacting and leaving the contact zone simultaneously [8].

The prediction errors on overall noise levels are rather small, less than 1 dBA on average. The consideration of combined air-pumping and tyre vibration contributions will be sought around the transition frequency for further reduction of this prediction error.

Lastly, the model should be applied to other impervious road surfaces for validation.

7. ACKNOWLEDGMENT

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