On site acoustic characterization of optimized very thin asphalt concretes

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Summary

This paper deals with *in situ* characterization of Very Thin Asphalt Concretes (VTAC) optimized for tyre/road noise abatement. Two sites have recently been tested in France, the first one paved with a five years old VTAC 0/4 and the second one paved with a one year old VTAC 0/6. The measurement campaign included tyre/road noise testing as well as assessment of road surface properties like 3D texture and sound absorption. Close-ProXimity (CPX) and Coast-By (CB) tyre/road noise measurements were performed simultaneously over a distance of 20 meters long. The test vehicle was a passenger car fitted with patterned tyres. Several runs were performed at steady speed from 40 km/h up to 110 km/h, leading to the estimation of CPX and CB noise levels and spectra at different reference speeds. The 3D texture of the road surfaces was evaluated with a newly developed device involving a 2D laser sensor. The texture sample size was about 0.35 m by 1.5 m with a sampling interval of 0.1 mm. A specific protocol was used to record four aligned texture samples with overlapping zones, leading to a final complete surface of about 6 m by 0.35 m. Texture data were processed to get the height probability densities, the mean texture depth as well as the raw and the enveloped longitudinal texture spectra. Sound absorption was also measured following ISO 13472-1 leading to absorption peaks around 1000 Hz for the VTAC 0/4 and around 800 Hz for the VTAC 0/6. The CPX and CB noise results of the tested road surfaces are compared to results for reference road surfaces, i.e. a VTAC 0/6 and a DAC 0/10 located on a reference test track. Noise performances of the optimized VTAC are finally discussed with regards to texture and sound absorption properties.

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1. Introduction

Low-noise road surfaces can be employed by the authorities to reduce noise at the source efficiently and meet the recommendations of the Environmental Noise Directive 2002/49/EC. Among the most promising solutions mentioned in [1], fine graded Very Thin Asphalt Concretes (VTAC) [2] as well as texture optimization of a dense pavements [3] have been identified as potential solutions for noise reduction.

Thus the German-French cooperative project ODSurf [4] aimed at assessing the acoustical performances of optimized VTAC developed by French road companies. The idea was also to compare these conventional road techniques with some optimized pavement structures (mainly based on new technologies) developed in Germany within the LeiStra 3 program.

Therefore, two VTAC test sections were tested in France. The first one was a five years old VTAC 0/4 and the second one was a one year old VTAC 0/6. The measurement campaigns included characterization of road surface properties like 3D texture and sound absorption as well as tyre/road noise, which are reported and discussed in the following.

2. Test sites and road pavements

The first test site was located on road D670 in Mouvaux in the north of France (Figure 1). The road was a 2 by 2 lanes suburban boulevard well suited for on site measurements. The traffic limit speed was 70 km/h. The test section was built in 2009 and was about 500 m long. It was paved with an acoustically optimized VTAC 0/4 of grading 4 mm with a network of very small regularly shaped communicating voids.

The second test site was located on road D911 near Villeneuve-sur-Lot in the south west of France (Figure 2). The road was a two lanes bypass well suited

Figure 1. VTAC 0/4 test section (left) and 10 by 20 cm top view of the road surface (right).

for on site measurements. The traffic limit speed was 90 km/h. The test section was built in autumn 2013 and was about 1 km long. The road surface was a VTAC 0/6 of grading 6 mm specifically designed and optimized for a longer lasting noise reduction.

Figure 2. VTAC 0/6 test section (left) and 10 by 20 cm top view of the road surface (right).

The measurement campaign was performed in July 2014 on VTAC 0/4 and in September 2014 on VTAC 0/6. The tests were carried out during the nighttime to limit background noise and traffic annoyance. Texture and absorption were measured in the same track as rolling noise for the VTAC 0/6 test site while it was not possible to do so for the VTAC 0/4 test site since only one lane was close to traffic during the tests. For the sake of comparisons, the same properties were characterized on two reference test sections located on Ifsttar test track in Nantes (France): a VTAC 0/6 built in 2006 and a Dense Asphalt Concrete (DAC) 0/10 built in 1981.

3. Road texture measurements

3.1. Equipment and measurement method

The texture measurement equipment is based on a 2D laser sensor that is moved over the road surface by a motorized linear axis (Figure 3). A positioning table is transversely fixed to the axis slide to allow the lateral positioning of the laser sensor.

The laser sensor delivers texture data as clouds of 640 points along a 50 mm long straight segment. The sensor is triggered by the displacement system every 0.1 mm. The profiles are recorded on a laptop using a dedicated software.

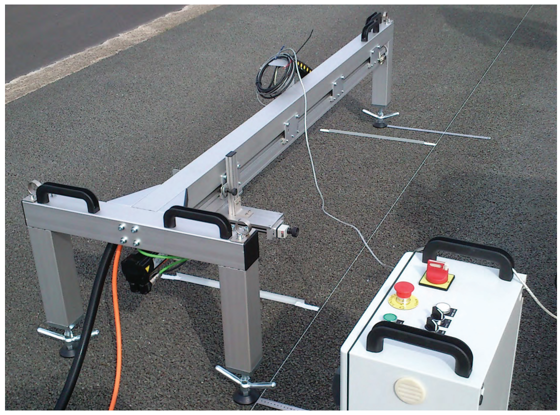

Figure 3. Texture measurement system. View of the chassis with the motor-driven linear axis and the control unit.

The texture measurements are performed in the CPX measurement wheel track. Once the system is adequately positioned on the road surface, parallel strips are measured for several lateral positions of the sensor in such a way that adjacent strips overlap.

Four complete aligned samples with 10 cm long overlapping zones are measured for each road surface with the use of a stretched wire ensuring a good alignment of successive positions of the chassis.

3.2. Data analysis method

Several algorithms have been developed to reconstruct a complete surface from the longitudinal strips for one chassis position on the one hand, and to connect successive overlapping complete recordings on the other hand. The final complete reconstructed surfaces are about 5.8 m long and 0.35 m wide. The longitudinal and transversal sampling intervals are 0.1 mm. Extracted 5 cm by 5 cm parts of the tested VTAC and both reference surfaces are shown in Figure 4 . Examples of 0.3 m long profiles are given in Figure 5.

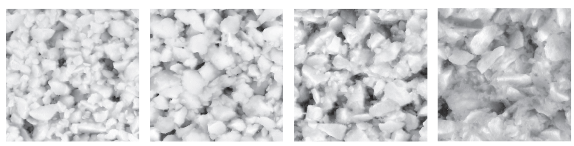

Figure 4. 50 mm by 50 mm samples of the surfaces (white color stands for asperities, black color for cavities). From left to right: VTAC 0/4, 0/6, 0/6 (ref), DAC 0/10 (ref).

Several texture related quantities were evaluated from the measurements:

- the Estimated Texture Depth (ETD), according to the ISO standard 13473-2,
- the height probability density averaged over 25 cm by 25 cm 3D texture samples,

- 1/3 octave band raw and "enveloped" texture spectra calculated from the longitudinal profiles.

The enveloped texture is intended to provide the part of the texture likely to enter into contact with the tyre [5]. It is used in the HyRoNE model [6] to predict the noise radiated by the tyre belt. Enveloped profiles are given in Figure 5 with the corresponding raw texture profiles.

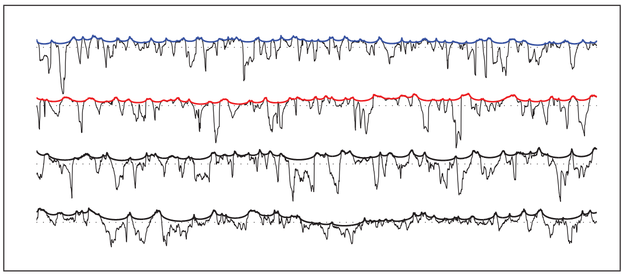

Figure 5. Raw and enveloped 0.3 m long texture profiles. From top to bottom: VTAC 0/4, 0/6, 0/6 (ref), DAC 0/10 (ref) (5 mm amplitude between horizontal dotted lines).

3.3. Texture results

The evaluated height probability densities are drawn in Figure 6 (left). Results for VTAC 0/4 and VTAC 0/6 are very close to each other. They present a typical negative texture distribution, together with VTAC 0/6 (ref), while the texture of the DAC 0/10 is more neutral. ETD values (Figure 6, right) are very close too for both tested VTAC (0.94 mm and 0.95 mm). For the reference surfaces, they are 1.3 mm and 1.13 mm.

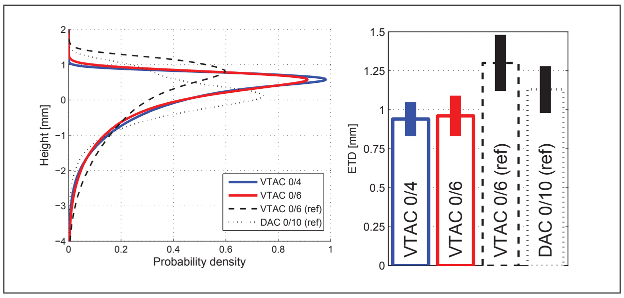

Figure 6. Left: Height probability densities. Right: ETD values and associated standard deviations.

The texture spectra are given in Figure 7 (left) for wavelengths ranging from 1 mm to 0.25 m. The difference between the tested VTAC texture spectra does not exceed 1.3 dB over the range considered. There is a slight wavelength shift probably due to the grain size difference. For wavelengths lower than 6 mm, the levels are very close to those of the reference VTAC and are about 5 dB higher than those of the reference DAC. For wavelengths higher than 20 mm, the levels are 5 dB lower than those of the reference VTAC whereas those of the DAC are in between.

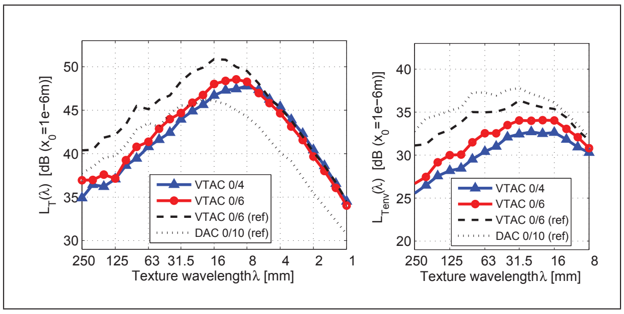

Figure 7. Third-octave texture spectra. Left: raw texture. Right: enveloped texture.

Concerning the enveloped texture spectra drawn in Figure 7 (right) for wavelengths between 8 mm and 0.25 mm, the VTAC 0/4 shows the lowest levels. Those of the VTAC 0/6 are between 1 and 2 dB higher. The reference DAC shows the highest enveloped texture levels due to its neutral texture.

4. Sound absorption measurements

4.1. Equipment and measurement method

Sound absorption was measured following the recommendations of ISO 13472-1. The equipment was a stationary system composed of a sound source and a microphone respectively positioned at a distance d_s and d_m above the road surface (Figure 8).

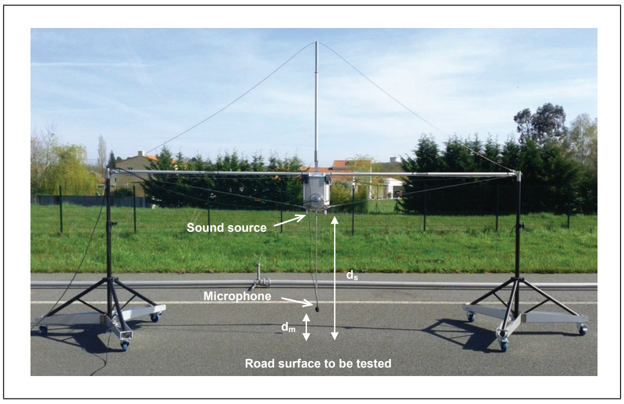

Figure 8. Sound absorption measurement system.

During the measurement, the source and the receiver were first positioned vertically with the microphone at the bottom. A white noise signal was driven through the loudspeaker and the signal/noise ratio was improved by repeating the acquisition and averaging the microphone response. Then the system was reversed vertically (microphone upward) to get the free field response which was subtracted from the downward time response in order to isolate the reflected contribution.

For a given test section, sound absorption was measured in the middle of the tested lane at five spots around the Reference Point (RP) used for noise measurements. The spacing between two consecutive spots was 2 m wide. For each spot, a free field measurement was performed.

4.2. Data analysis method

The measurement method is based on the determination of the incident H_i and the reflected H_r frequency transfer functions between the source and the receiver, which can be evaluated from the separation of the impulse responses of the direct and the reflected paths in the time domain. The narrow bandwidth sound absorption coefficient $\alpha(f)$ is calculated as follows:

$$\alpha(f) = 1 - \frac{1}{K_r^2}\left|\frac{H_r(f)}{H_i(f)}\right|^2, \tag{1}$$

with f the frequency and $K_r = (d_s - d_m)/(d_s + d_m)$ a correction factor. The sound absorption coefficient can then be easily obtained in 1/3 octave bands.

The absorption coefficient in Eq. 1 was fitted to the predictive model [7] in order to assess the physical parameters of the road surface. The absorption coefficient at normal incidence can be expressed from the normalized specific surface impedance Z:

$$\alpha = 1 - \left|\frac{Z-1}{Z+1}\right|^2. \tag{2}$$

Assuming a perfectly rigid bottom layer, $Z = Z_c \coth(-ikl)$ with Z_c the characteristic impedance of the road structure, k the complex wave number of the porous pavement and l the thickness of the porous layer. In [7], Z_c and k are calculated from three physical parameters which are the communicating porosity Ω, the specific flow resistance R_s and the non-dimensional shape factor q^2.

4.3. Sound absorption results

For each road surface, the absorption coefficient was first measured at the five spots and averaged in the narrow bandwidth frequency domain. Then the 1/3 octave band sound absorption coefficient was calculated. The results are given in Figure 9 and show wide absorption peaks. VTAC 0/4 has an absorption peak at 1000 Hz with $\alpha = 0.59$ while the peak for VTAC 0/6 is located at 800 Hz with $\alpha = 0.44$. Peaks for these two surfaces are higher and more pronounced than the peak at 1000 Hz for the reference VTAC 0/6.

Additionally, the predictive model was fitted to the averaged narrow bandwidth absorption curve. The parameters Ω, R_s and q^2 were adjusted manually in order to get the best agreement between measurement

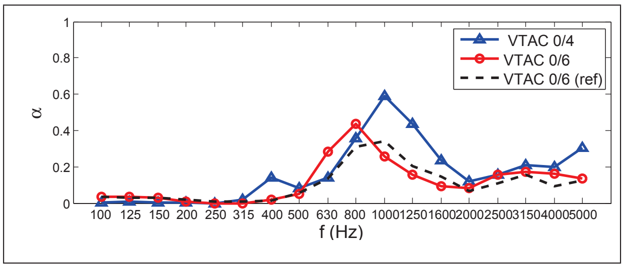

Figure 9. Comparison of sound absorption coefficient α.

and model on the first absorption peak. The thickness l was chosen as the theoretical value at the construction. The parameters are given in Table I.

Table I. Parameters of the predictive absorption model.

Road surface	l (m)	Ω	R_s (Nm^{-4}s)	q^2
VTAC 0/4	0.03	0.18	110000	5.5
VTAC 0/6	0.03	0.13	165000	9.7
VTAC 0/6 (ref)	0.025	0.12	270000	10

5. Tyre/road noise measurements

5.1. Equipment and procedure

Close-ProXimity (CPX) and Coast-By (CB) measurement methods were used simultaneously to characterize tyre/road noise over 20 m of the road section (Figure 10).

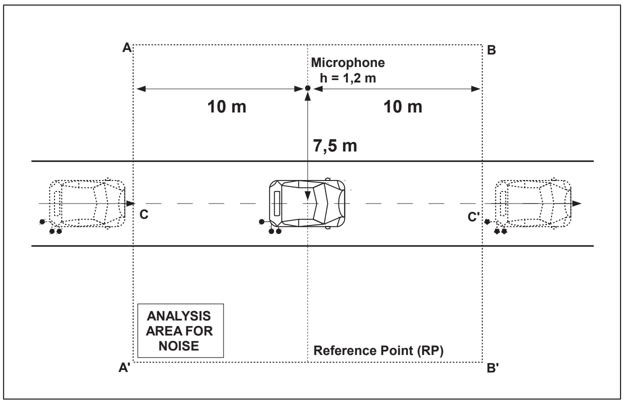

Figure 10. Tyre/road noise measurement procedure.

The procedure followed the recommendations of EU Directive 2001/43/EC. The vehicle was coasting at a constant speed through the test area between lines AA' and BB'. The transmission was put in neutral immediately before the vehicle reaches line AA' in order to reduce engine noise. Several runs were performed every 5 km/h at steady speeds V from 40 to 90 km/h on VTAC 0/4 and from 40 to 110 km/h on VTAC 0/6. The speed ranged between 65 and 110 km/h for the reference road surfaces (VTAC 0/6 and DAC 0/10).

The test vehicle was a passenger car Renault Scénic fitted with four identical patterned tyres Michelin Energy E3A 195/60 R15. The inflation pressure was 0.22 MPa and the shore A hardness was about 72.

CPX noise measurements were performed according to the French method described in [8]. Three microphones are fitted near the rear right wheel (Figure 11): microphones 1 and 2 are located at lateral positions specified in ISO/DIS 11819-2, while microphone 3 is positioned in the median plane behind the tyre. The acquisition system is automatically triggered via an infra-red switch. The test section is sampled in segments of length $\Delta x = 1.88$ m corresponding to one wheel rotation. The vehicle speed $V(\Delta x)$, the overall A-weighted equivalent noise level $L_{Aeq,i}(\Delta x)$ and the 1/3 octave band noise level $L_{eq,i}(\Delta x, f)$ at each microphone i are recorded for each position Δx.

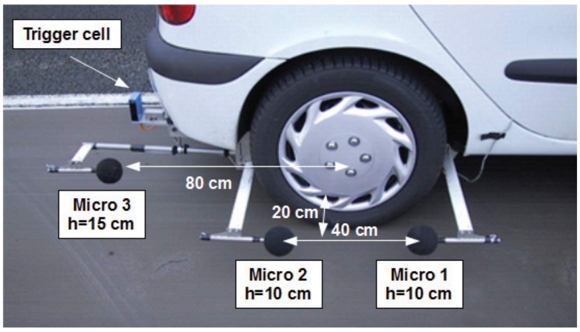

Figure 11. CPX measurement system.

CB noise measurements were performed according to EU Directive 2001/43/EC, but here only one microphone was used on the road side. It was located at 7.5 m from the middle of the tested lane and 1.20 m above the ground. The average speed between lines AA' and BB' was obtained from the CPX system. For each run, the acoustic signal was recorded by means of a digital audio recorder and processed using a dedicated software dBEuler 2.0 [9]. According to ISO 11819-1, for each vehicle pass-by the maximum A-weighted sound pressure level L_{Amax} was taken as the maximum of the fast time-weighted sound level. 1/3 octave band noise levels $L_{max}(f)$ between 100 Hz and 5 kHz were also captured at the instant of the maximum.

5.2. Tyre/road noise analysis method

Coast-By noise levels were analysed trough a logarithmic regression versus speed:

$$L_{Amax}(V) = a_{L_{Amax}} + b_{L_{Amax}} \log_{10}(V), \qquad (3)$$

where $a_{L_{Amax}}$ is a constant value in dB(A) and $b_{L_{Amax}}$ is a slope in dB(A) per decade of speed. The same speed dependency was assumed for 1/3 octave noise levels (in dB) at frequency f:

$$L_{max}(V, f) = a_{L_{max}}(f) + b_{L_{max}}(f) \log_{10}(V), (4)$$

Thus noise data can be analysed by means of a logarithmic regression on the experimental data. The 95% confidence interval of the parameters can also be calculated.

Analysis of CPX noise levels requires attention since it has been shown by [10] that the measurements may be polluted by wind noise below 400 Hz and above 4000 Hz. Therefore, the arithmetic average of CPX noise levels on lateral microphones 1 and 2 was first recomposed in the valid frequency range:

$$L_{Areq}(V) = 10 \log_{10} \left(\sum_{f=400Hz}^{4000Hz} 10^{\frac{L_{Aeq}(f)}{10}} \right), \quad (5)$$

and then a logarithmic regression was performed to identify $a_{L_{Areq}}$ and $b_{L_{Areq}}$ similarly to Eq. (3). A logarithmic regression was performed on the 1/3 octave CPX noise levels at frequency f, similarly to Eq. (4).

5.3. Noise results

CPX and CB noise results are presented in Table II at the reference speed of 70 km/h. The 95% confidence interval of the prediction is also indicated. No temperature correction was applied since the measurements were all performed at about 15°C. The CPX noise level for the VTAC 0/4 is very close to the reference VTAC 0/6, while the VTAC 0/6 is 1.4 dB(A) lower. Comparing to the reference DAC 0/10, the noise reduction is 2.1 dB(A) for the VTAC 0/4 and 3.5 dB(A) for the VTAC 0/6. The regression slopes for the tested VTAC 0/4 and VTAC 0/6 are surprisingly high for semi-porous asphalt. CB results show that on the road side, the noise levels for the VTAC 0/4 and 0/6 are respectively reduced from 1.0 to 1.6 dB(A) in comparison with the reference VTAC 0/6 and from 5.0 to 5.6 dB(A) in comparison with the reference DAC 0/10. The higher noise reduction in comparison with CPX is mainly due to sound absorption along the propagation path. This is highlighted by higher difference between CPX and CB noise levels for the VTAC than for DAC 0/10. The regression slopes for the tested VTAC 0/4 and VTAC 0/6 are still high and close to the value for the DAC 0/10.

Figures 12 and 13 give the 1/3 octave band noise spectra respectively for CPX and CB methods. Noise levels of VTAC 0/4 and VTAC 0/6 (ref) are very close and attenuated after 800 Hz due to absorption peak at 1000 Hz (Fig. 9) and high texture levels at wavelengths below 8 mm (Fig. 7, left) decreasing air-pumping. Below 1000 Hz, VTAC 0/4 is quieter than

Table II. Comparison of overall noise levels at 70 km/h and regression slopes.

Road surface	$L_{Areq}(70)$ (dB(A))	$b_{L_{Areq}}$ (dB(A)/dec)	$L_{Amax}(70)$ (dB(A))	$b_{L_{Amax}}$ (dB(A)/dec)
VTAC 0/4	**93.6** ± 1.3	40.8 ± 1.1	**69.6** ± 0.7	33.6 ± 2.1
VTAC 0/6	**92.2** ± 1.5	32.8 ± 0.8	**69.0** ± 1.0	32.3 ± 1.7
VTAC 0/6 (ref)	**93.5** ± 1.0	23.0 ± 1.2	**70.6** ± 1.0	22.4 ± 4.0
DAC 0/10 (ref)	**95.7** ± 0.9	33.7 ± 1.0	**74.6** ± 1.0	32.0 ± 4.0

VTAC 0/6 (ref) due to smaller enveloped texture levels (Fig.7, right) providing less tyre vibrations. Noise levels for VTAC 0/6 are smaller than for VTAC 0/4 below 1250 Hz due to absorption peak at 800 Hz (Fig. 9), which frequency corresponds to the periodicity of the tyre tread block impacts at 70 km/h. Thus the CB spectra for VTAC 0/6 has a flat shape until 2000 Hz, as one can typically observe for a slick tyre.

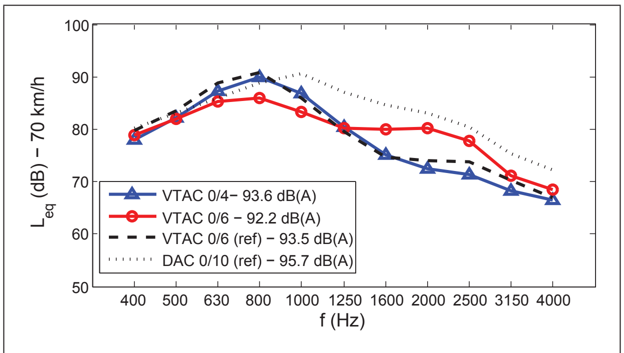

Figure 12. CPX noise spectra at 70 km/h.

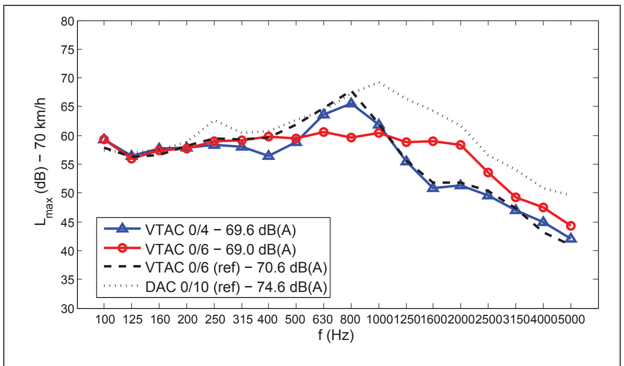

Figure 13. CB noise spectra at 70 km/h.

6. Conclusions

In this paper, the performances of two VTAC optimized for rolling noise abatement have been assessed from *in situ* measurements of 3D road texture, sound absorption as well as CPX and CB tyre/road noise. Enveloped texture levels of the tested VTAC are highly reduced at wavelengths above 8 mm in comparison with reference road surfaces. Sound absorption measurements also show high absorption peaks at 1000 Hz for VTAC 0/4 and 800 Hz for VTAC 0/6. These properties can be related to the shapes of the noise spectra. For the VTAC 0/4 test section, overall noise levels at 70 km/h show a reduction from 2.1 dB(A) (CPX) to 5.0 dB(A) (CB) in comparison with the reference road surface DAC 0/10. The reduction is even better for the VTAC 0/6 test section, with noise abatement ranging between 3.5 dB(A) (CPX) and 5.6 dB(A) (CB). Future work will aim at using the measured properties (texture, absorption) to assess the capacity of tyre/road noise models to predict rolling noise for these road surfaces.

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