Road texture and rolling noise: an envelopment procedure for tire-road contact

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Bibliographic notice

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Texture is a meaningful information for the noisiness evaluation of road pavements. An envelopment procedure has been developed at INRETS to take into account the interaction between the tire and the road surface. It uses a static contact model with one parameter. A special attention is given on how to avoid the edge effects due to the finite length of the texture samples. This procedure is here applied to a few road pavements.</td></tr>
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La texture est une information importante pour l'évaluation acoustique d'un revêtement routier. Une procédure d'enveloppement a été développée à l'INRETS pour prendre en compte l'interaction entre le pneumatique et la surface de chaussée. Elle utilise un modèle de contact statique à un paramètre. Une attention particulière est portée à la manière d'éviter les effets de bord dus à la longueur finie des relevés de chaussée. Cette procédure est appliqué ici à quelques revêtements.</td></tr>
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Contents

1 – Introduction

Experimental and statistical approaches aiming at providing the relations between pavement characteristics and tire-road noise ([1]) are mixed with physical models to obtain more accurate prediction tools which do not depend on the type of the considered pavements ([2], [3], [4]).

It is acknowledged that the road texture profile plays a fundamental role in the tire road noise generation. The same is true for the tire tread pattern. It can be intuitively reckoned that tires with "aggressive" tread patterns rolling on tather smooth road surfaces will generate a tire road noise somewhat independently of the road texture profile, while tires with non "aggressive" tread patterns rolling on highly texture roads, will generate a tire road noise almost independently of their tread patterns. This must be kept in mind when evaluating the road texture influence on tire noise: below a certain road texture level, the influence of the tire pattern becomes predominant.

The characterisation of the road texture is not as simple as it may seem: taking abruptly the spectrum of the measured profile gives as much weight to the ridges as it does to the valleys. No difference is made in particular between two mirror profiles. The profiles shematised in figure 1.1 would correspond to an alert band mark painting (left graph) and a cobblestone type pavement (right graph). The first is considered more aggressive and noisy than the second. On a texture spectrum basis they are identical. This

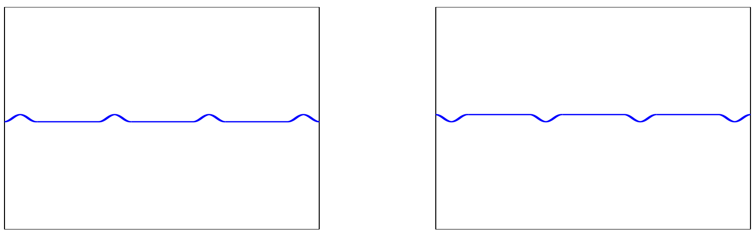


Figure 1.1: Illustration of two mirror images of a road profile

means that tire noise predictions based on the road spectrum would wrongly conclude that both pavements are acoustically identical. The other way around, comparison between the noise and road spectra would as wrongly conclude that tire noise does not depend on road texture, since two identical road spectra result in two different noise spectra.

It is believed that this may be part of the problems encountered with porous pavements, which show pronounced dips. Beyond some depth, the tire vibrations are no more affected by a further depth increase, while the texture level still is.

A possibility to take this into account is to "envelope" the road profile before evaluating the spectrum. A simple smoothing of the data has been suggested but does not seem to have given entire satisfaction to its authors [2]. It seems that the envelopment should somewhat reflect the actual deformation of the tread gum in the contact zone as the contact model proposed by Clapp [3]. These two approaches are briefly described in Part 2.

The contact model developed and used at INRETS is then presented in Part 3 and applied to some road pavements [5] in Part 4.

2 – State of the art

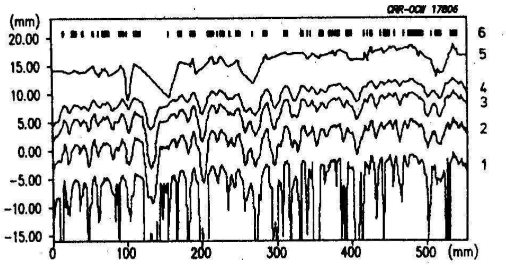
Here we briefly describe two envelopment procedures used for tire-road noise purpose. The first one was proposed by von Meier and al. [2] and the second by Clapp [3].

2.1 Von Meier and al. procedure

This envelopment method is not based on a physical model. It is an empirical procedure based on the mathematical limitation of the second-order derivative of the discretized texture sample as follows

$$\frac{y_i - \frac{y_{i-1}+y_{i+1}}{2}}{dx^2} \leq d^* ,$$

where y_i is the amplitude of the profile for index i, dx the sampling step and d^* the parameter which characterises the tire stiffness. It results in a parabola shape penetration of the rubber into the texture cavities (see figure 2.1).



(1) A typical texture profile as recorded by the laser profilometer on a porous road surface. (2,3,4) Envelope of (1) computed by means of the algorithm shown on Fig.7 with d =.108/.054/.027 respectively. (5) Profile obtained from (1) when drop-outs are restored by linear interpolation. (6) Light intensity record where blanks denote drop-outs.

Figure 2.1: Example of enveloped profiles obtained by Von Meier and al. algorithm for different values of d^* (from [2])

The output of this procedure is an enveloped profile: no information is given on the contact forces developed at the interface.

Von Meier and al. [2] used these enveloped profiles to perform an approach similar to that performed by Sandberg and Descornet [1] for finding enveloped-texture/noise relationships. The value of the parameter d^* was obtained from measurements of the deformation of a tire pressed onto different profiles. This value was chosen for this study to be $d^* = .054mm^{-1}$.

2.2 Clapp's model

Clapp's envelopment procedure [3] is based on a physical model. It consists in evaluating the contact between a rigid body (indentor) and a semi-infinite elastic body.

2.2.1 The contact problem

The semi-infinite elastic body is characterized by its Young modulus E and Poisson coefficient ν. Assuming that the elastic body has rubber characteristics, ν is taken to be equal to 0.5.

The problem consists in finding the displacement of the frontier of the elasic body when an indentor is applied with a given normal load (see figure 2.2). According to the linear road texture description, the problem to be solved is bi-dimensionnal.

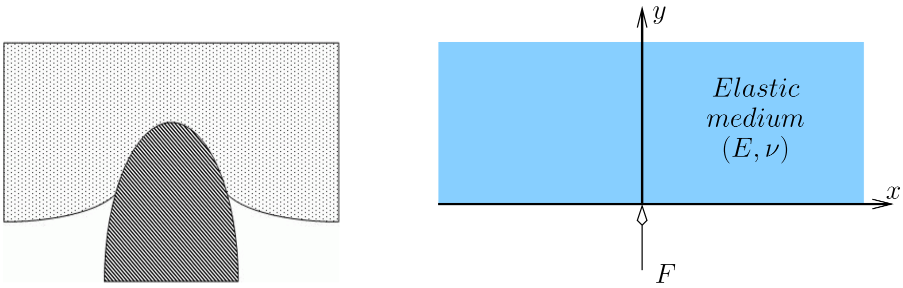


Figure 2.2: The indentation problem - Notations

2.2.2 Clapp's formulation and algorithm

The vertical displacement $u(x)$ of the frontier of the elastic body due to a pressure distribution $p(x)$ [1] is obtained by using the linear elasticity equations:

$$\frac{\pi E u(x)}{2(1-\nu^2)} + c_0 = -\int_a^b p(\xi) ln|\xi - x| d\xi \, , \tag{2.1}$$

where c_0 is a constant to be determined and a and b the limits of the contact zone.

The global equilibrium of the system is written as

$$\frac{1}{b-a}\int_a^b p(x)dx = P \, , \tag{2.2}$$

where P is the mean pressure applied on the elastic body.

The difficulty for solving the problem lies in its geometrical non-linearity which means that the part of the indentor in contact with the rubber is unknown.

The principle of Clapp's algorithm is based on two procedures.

The first procedure permits to obtain the texture-induced pressure distribution using equation 2.1 assuming that the rubber displacement $u(x)$ is known. This so-called approximation method consists in cubic spline discretization of the interface and the inversion of equation 2.1 to determine the pressure distribution from $u(x)$.

The second procedure permits to evaluate the mean penetration depth of the rubber into texture asperities using equation 2.2 to get an approximated rubber displacement to be used in the approximation method.

Computing limitation requires each profile to be divided in sub-profiles with overlapping sections. The method permits to determine the pressure distribution along the texture profile. To get the enveloped profile, straight lines are drawn between consecutive

[1] All equations are written for a unitary width in the direction perpendicular to the plane (x,y). The factor 1 is omitted.

asperities of non totally enveloped valley . The true rubber displacement is never reached, it seems that the pressure distribution is obtained only approximately. An example of result is given in figure 2.3.

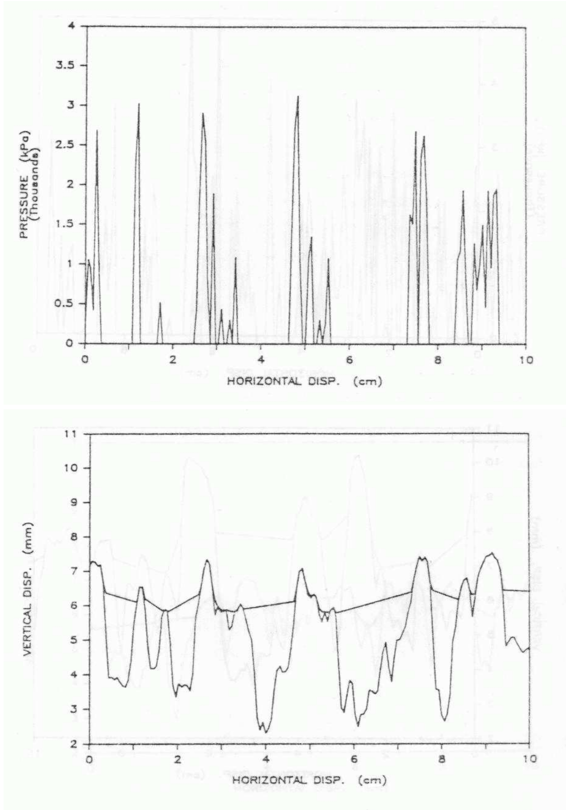


Figure 2.3: Example of pressure distribution and enveloped profile obtained by Clapp's algorithm (from [3])

The contact information used by Clapp to study the texture/noise relationship was the pressure distribution spectra. The distance scale of texture profiles was transformed to time scale introducing the velocity V of the vehicle to obtain pressure spectra as a function of time frequency $f_{time} = V/\lambda_{texture}$.

3 – INRETS model

3.1 Formulation

The vertical displacement δu of the frontier of the elastic body due to a normal punctual force δF at point $x = 0$ can be calculated as (see figure 2.2 for the notations)

$$\delta u(x) = -\frac{2(1-\nu^2)}{\pi E} \ln |x| \delta F + \alpha \; .$$

Green's formalism is here used to express the displacement at point x with respect to the displacement of a reference point x_0 as

$$u(x) - u(x_0) = \int_{(C)} [g(x,\xi) - g(x_0,\xi)]\, p(\xi) d\xi \; , \tag{3.1}$$

where (C) is the contact zone, p the pressure distribution on (C) and g the Green's function of the problem given by

$$g(x,\xi) = -\frac{2(1-\nu^2)}{\pi E} \ln |x - \xi| \; .$$

The global equilibrium of the system is written as

$$\frac{1}{L} \int_{(C)} p(x) dx = P \; , \tag{3.2}$$

where P is the mean pressure applied on the elastic body, L the length of the sample.

3.2 Algorithm

The interface is discretized in elements of equal length. According to Green's formalism, equation 3.1 permits to calculate influence coefficients giving the displacement of each element when a unit force is applied on any one. The contact zone (C), the pressure distribution $p(x)$ and the rubber displacement $u(x)$ are determined using an iterative algorithm which ensures that the contact forces balance the prescribed load and that $p(x)$ is positive when the contact occurs. The algorithm rapidly converges and guarantees a perfect fitting between the pressure distribution and the displacement through equation 3.1.

3.3 Edge effect

Edge effect appears when using finite length samples. This can be seen in the pressure distribution over a smooth plane profile (figure 3.1): whatever the length of the profile numerical evaluations using a finite length profile yields overpressures at the edges and a corresponding underpressure in the middle of the profile.

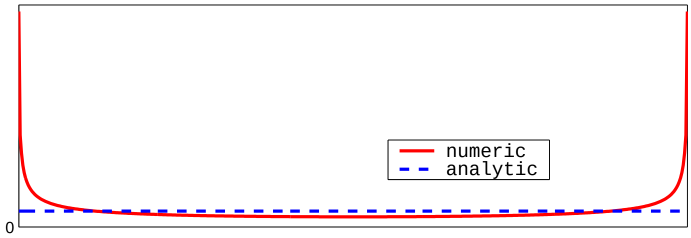


Figure 3.1: Pressure distribution for a smooth plane profile

3.4 The periodic contact model

To avoid edge effects the problem is periodicized. This comes down to consider a periodic profile created by an infinite repetition of the given profile. It means that each point is influenced by the pressure acting on the main profile and on all repeated profiles. It is equivalent to consider a Green's function G as the sum of contributions of the Green's function g shifted of integer multiple of L:

$$G(x,\xi) = \sum_{n=-\infty}^{+\infty} g(x, \xi - nL)\,. \tag{3.3}$$

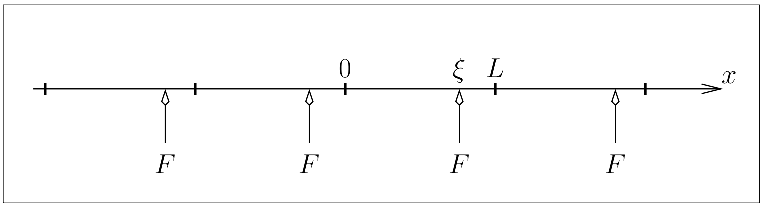


Figure 3.2: Calculation of the periodicized Green's function

4 – Application of INRETS model to texture profiles

INRETS model yields the pressure distribution as well as the rubber displacement. Three examples are given in figures 4.1 and 4.2 corresponding to a cement concrete, a bituminous concrete and a porous asphalt. The smaller the Young's modulus, the deeper the penetration, the larger the contact area and the smoother the pressure distribution.

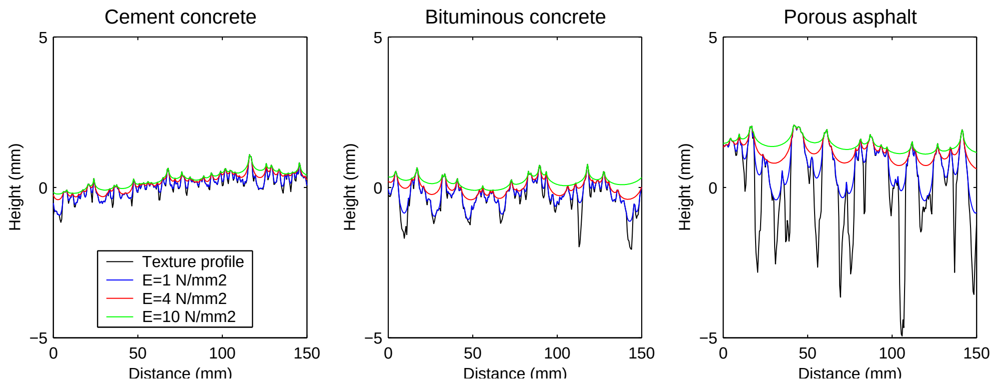


Figure 4.1: Enveloped profiles for three road pavements and different values of Young's modulus

A comparison of the rubber displacement as obtained with von Meier and al. [2] procedure and with INRETS procedure is given figure 4.3. As can be seen the hierarchy between the depth of penetration obtained with both procedures is not always the same along the profile. It depends on the width of the valley between two consecutive asperities. For the widest valleys the penetration depth obtained with von Meier and al. procedure ranges between the penetration depth obtained with INRETS procedure with Young's modulus values of $E = 5N/mm^2$ and $E = 10N/mm^2$ while for the narrowest it ranges between those obtained with $E = 1N/mm^2$ and $E = 2N/mm^2$.

4.1 Influence on texture spectra

To assess the influence of the envelopment procedure on texture profiles in terms of spectral components, texture spectra are calculated from the enveloped profiles and drawn figure 4.4. Differences with respect to the road texture profile are also drawn. It clearly appears that the envelopment procedure reduces the "depth effect" on pavements like porous asphalts: on these pavements the presence of pores yields high texture levels in the entire range of interest.

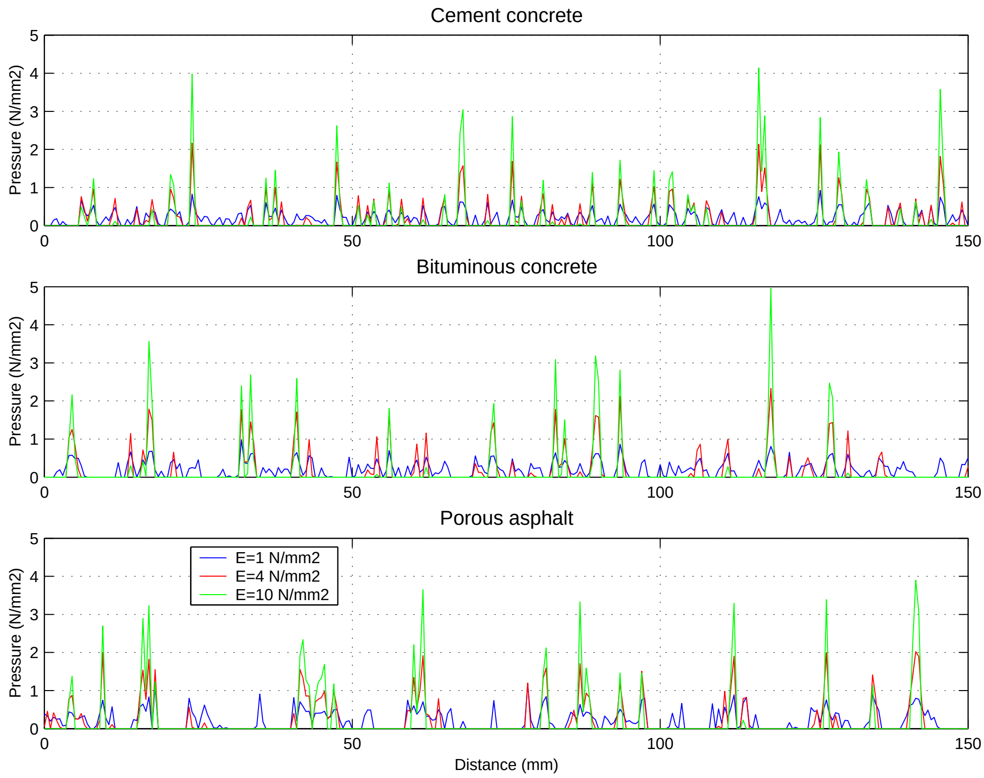


Figure 4.2: Pressure distributions for three road pavements and different values of Young's modulus

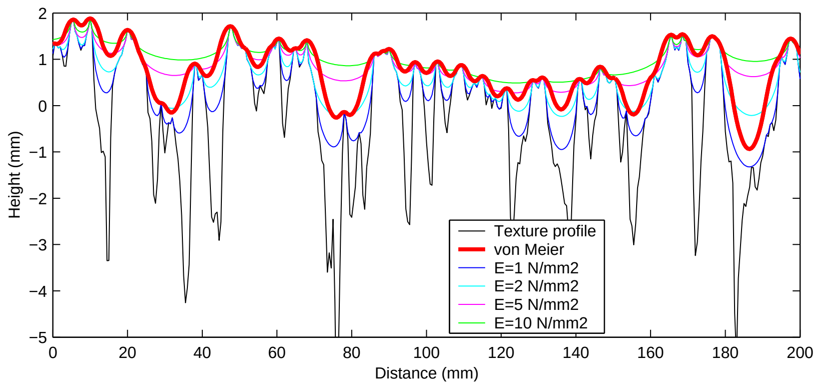


Figure 4.3: Comparison between von Meier's procedure ($d^* = .054mm^{-1}$) and INRETS procedure (different values of E)

4.2 Enveloped texture or contact forces?

The envelopment procedure provides two informations: the enveloped profile which is seen by the tire (rubber displacement) and the pressure distribution (or contact forces) developed at the interface. What is the most relevant information to be related to rolling noise spectra? The calculated pressure spectra corresponding to the enveloped profiles are drawn figure 4.5.

For each frequency band, the pressure levels are drawn figure 4.6 as a function of the

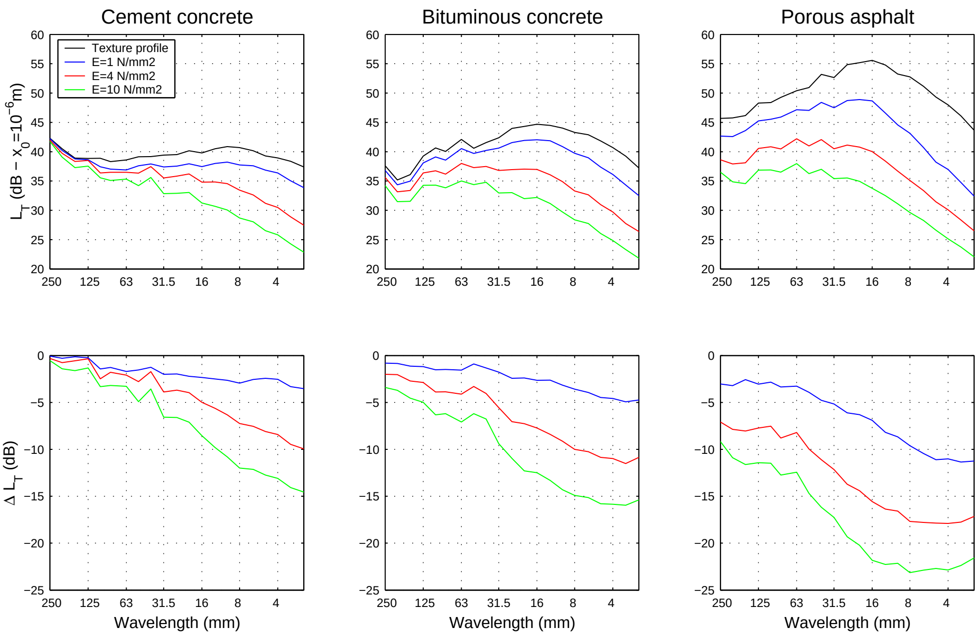


Figure 4.4: Texture spectra of enveloped profiles. Top: Absolute values - Bottom: Differences with respect to the original road texture profile

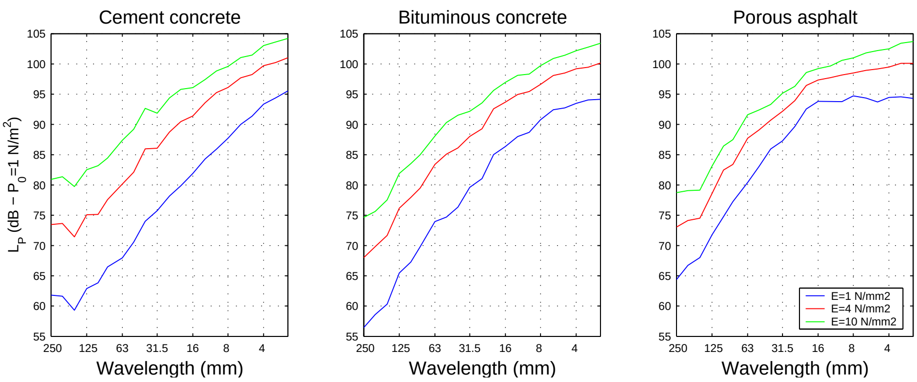


Figure 4.5: Pressure spectra of enveloped profiles.

texture levels (each point represents one road pavement). For each given value of the Young's modulus used in the envelopment, there is a linear relationship between pressure and texture levels of the enveloped profiles (for this set of pavements). This means that either texture or pressure spectra could be used to find the relationship between texture and noise.

Using texture spectra instead of pressure spectra permits the comparison between enveloped and original road profiles spectra and yields a better information about the benefit of the envelopment procedure.

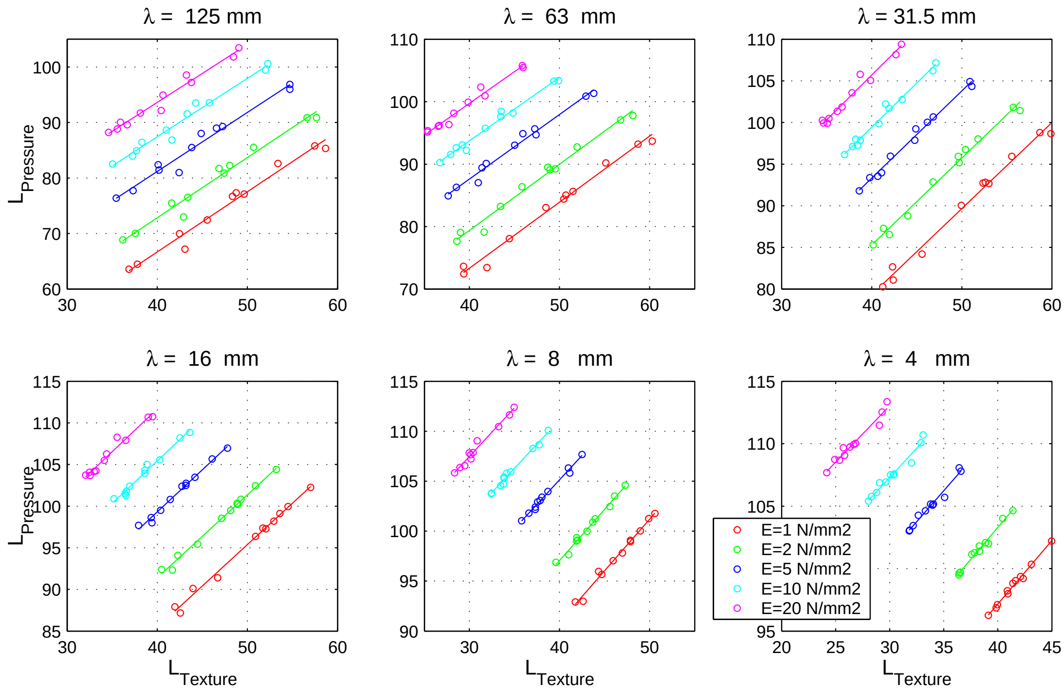


Figure 4.6: Pressure spectra vs texture spectra of enveloped profiles (octave bands). Each color represents one value of E (regression lines are associated to one color.)

5 – Conclusion

The static contact model described in this report was developed to extend the texture-noise relationships to surfaces such as porous asphalt in the frequency range where tire belt vibration noise predominates. It could be also helpful to evaluate the strengh of sources due to air-pumping phenomenon ([6] and [7]).

Using this model requires the determination of a single parameter: the Young's modulus E (the prescribed mean pressure is given by the tire inflation pressure). It can be taken as being the tire rubber Young's modulus. Another approach consists in finding the parameter value wich gives the best texture/noise correlations in noise frequency ranges where the acoustical absorption properties of the road pavements have no significant effect.

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