Road stiffness influence on rolling noise: Parametric study using a rolling tire model

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13 Summary
The influence of the road mechanical stiffness on tire road noise has been a research subject since the late 70's. Research efforts have addressed principally the measurement procedures of the road mechanical stiffness and the development of poro-elastic surfaces, including implementation on pilote sites. This report is an attempt to quantify the influence of this mechanic stiffness on tire road noise. The estimation is performed by simulation using a rolling tire algorithm developed at INRETS. The stiffness of present pavements is much larger than the tire sicknesses. It appears that a reduction of this pavement stiffness could reduce substantially the rolling noise. For his, the pavement stiffness must be of the same order of magnitude than the pavement stiffness (pavement stiffess/tire stiffness <10). The noise reduction would be practically independent of speed and could reach 5 dB(A). The reduction appears to occur mainly at medium and high frequencies.

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13 Résumé
L'influence de la rigidité mécanique de la chaussée sur le bruit de roulement est un thème qui a été abordé dès la fin des années 70. Les recherches ont porté principalement sur les méthodes de mesure de cette rigidité mécanique et sur la mise au point de revêtements élastiques (poroélastiques essentiellement) allant jusqu'à la mise en oeuvre sur sites pilote.)
Ce rapport tente de quantifier l'influence de la raideur mécanique du revêtement sur le bruit de roulement. L'estimation est effectuée par simulation en utilisant un algorithme de pneumatique en roulage développé à l'INRETS. Seule la part du bruit de roulement associée aux rayonnement vibratoire du pneumatique est prise en compte.
Les revêtements actuels ont une rigidité mécanique très importante par rapport à celle du pneumatique. Il apparaît qu'une réduction de cette rigidité mécanique pourrait réduire le bruit de roulement de façon substantielle. La raideur de la chaussée doit pour cela atteindre l'ordre grandeur de celle du pneumatique (raideur chaussée/ raideur pneu < 10). La réduction serait pratiquement indépendante de la vitesse et pourrait atteindre 5 dB(A). Elle ne serait significative qu'aux fréquences medium et aiguës.

14 Mots-clés bruit de roulement, rigidité de la chaussée, simulation	15 Diffusion **LIBRE** INRETS/RR/04-541-ENG

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Contents

1 – Introduction

Part of the modelling work in the SILVIA project is to help establish relations between intrinsic and functional acoustic properties of road surfaces. It is not intended to evaluate absolute noise levels but to translate road characteristic variations in actual noise variations and classify pavement characteristics in terms of potential noise generation or reduction. One of these acoustic properties is the mechanical stiffness.

The influence of the road mechanical stiffness on tire road noise has been a research subject since the late 70's. Research efforts have addressed principally the measurement procedures of the road mechanical stiffness and the development of poro-elastic surfaces, including implementation on pilote sites.
This report is an attempt to quantify the influence of this mechanic stiffness on tire road noise. The estimation is performed by simulation using a rolling tire algorithm developed at INRETS.
The stiffness of present pavements is much larger than the tire sicknesses. It appears that a reduction of this pavement stiffness could reduce substantially the rolling noise. For his, the pavement stiffness must be of the same order of magnitude than the pavement stiffness (pavement stiffess/tire stiffness <10). The noise reduction would be practically independent of speed and could reach 5 dB(A). The reduction appears to occur mainly at medium and high frequencies.

2 – State of the art

2.1 Stiffness: characteristics and measurements

Mechanical properties of the pavement with respect to vibrations have been characterized by the mechanical impedance $Z(x - x_o) = F(xo)/V(x)$ or its reciprocal, the mobility $Y(x - x_o) = V(x)/F(x_o)$, where F is the force input to the pavement and V the resulting velocity. When the velocity is taken at the impact position we shall talk about **driving point impedance**, or **driving point mobility** otherwise we shall talk about **transfer impedance** or **transfer mobility** [1]. The quantities can be expressed in dB:

$$L_Z = 20 \log \frac{F/F_o}{V/V_o} \qquad L_Y = 20 \log \frac{V/V_o}{F/F_o} \tag{2.1}$$

with $F_o = 1$ N and $V_o = 1$ m/s.

Bennerhult measured the driving point impedance over a variety of road surfaces using an impact hammer [1]. The velocity was taken at a short distance ($\sim$ 25 mm) from the impact. He estimated the measurement accuracy to be 1.5 dB. The values obtained over a variety of road surfaces ranged from 90 dB to about 115 dB (Fig 2.1). The influence of the transducer distance could not be established.

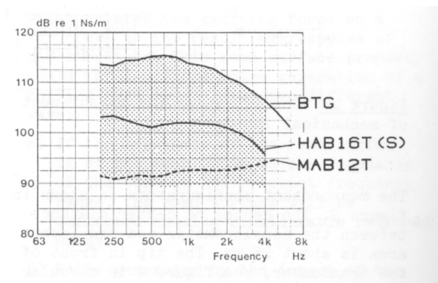

Figure 2.1: Mechanical impedance of road surfaces. Surfaces with high impedance in the high frequency domain [1]

Using also an impact hammer Lucquiaud measured the transfer mobility as a function of distance: the driving point impedance "informs us about how the road surface is able to resist or to absorb vibrations" while the transfer impedance informs "about the vibration transmission ability of the road surface" [2].

2.2 Stiffness effect: observations

Bennerhult concludes his investigations by stating that high mechanical impedance could increase the pass by noise level in the frequency domain 2 kHz - 5 kHz (although he wonders

[1] Throughout this report force and velocity are taken normal to the road surface, assumed to be flat

whether the impedance measurement technique is reliable at these high frequencies) [1].

Using all the measured data and plotting the residuals $Res(f_h/\lambda_h)$ (i.e. the deviation of the individual points from the regression line, when acoustical pass by levels $SPL(f_h)$ are regressed on road texture levels $RTL(\lambda_h)$) Sandberg [3] finds no correlation at all with one exception: the much stiffer concrete pavement also gives the maximum residual (Fig 2.2). He considers that the explanation corresponds to a combination of three possibilities:

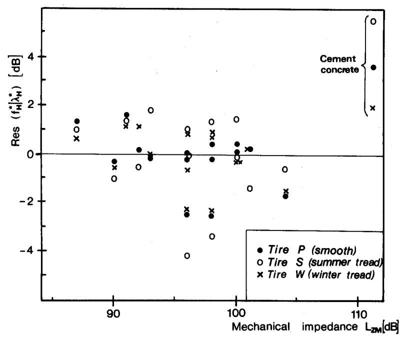

Figure 2.2: The residuals as a function of the mechanical impedance level (dB ref 1Ñs/m) at 2000 Hz [3]

1. there is no correlation between mechanical impedance and noise except for very stiff roads like the concrete
2. mechanical impedance is not an appropriate measure
3. there is a correlation between mechanical impedance and noise, but the measurement method is not appropriate, or too inaccurate

From the transfer mobility measurements (Fig 2.3) Lucquiaud [2] observes that the ranking according to mobility values is similar to ranking according to absorption properties and noise level assessment.

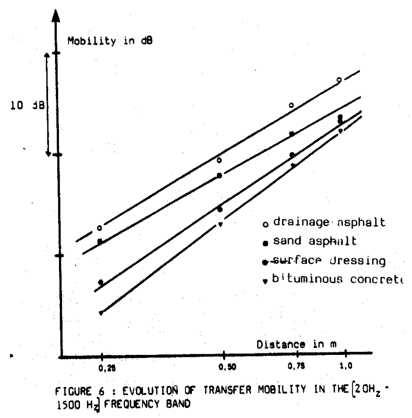

Figure 2.3: Evolution of the transfer mobility in the [20 Hz - 1500 Hz] frequency band [2]

Cement concrete pavements were usually noisier than asphalt concrete pavements. The explanation generally put forward was that a cement concrete has a higher mechanical impedance than an asphalt concrete. Descornet showed however that when taking macro- and megatexture into account, the apparent systematic difference of noisiness between cement-bound and bituminous-bound pavements is due to the former having higher levels of megatexture than the latter at equal macrotexture level (Fig 2.4 [4]). Moreover, he considers than due to progress made on how to optimize cement concrete wearing courses regarding noise, cement concrete may not be today noisier than asphalt concrete [5].

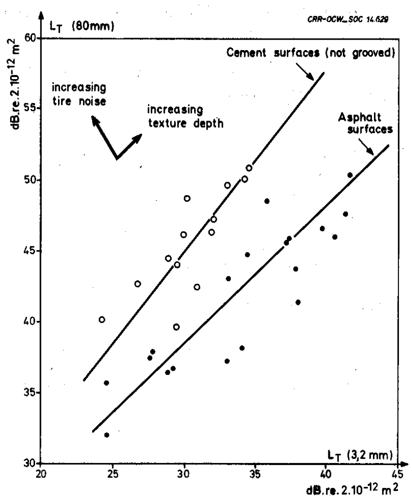

Figure 2.4: Comparison between asphalt and cement concrete surfaces based on their texture levels at the critical wavelengths with respect to tire/road noise [4]

Beckenbauer [6] performed coast by measurement on a sandpaper placed on a cement concrete, directly and with a soft rubber inter-layer. The insertion of the elastic material reduces the tire noise by about 5 dB in the mid frequencies (Fig 2.5 from [7]).

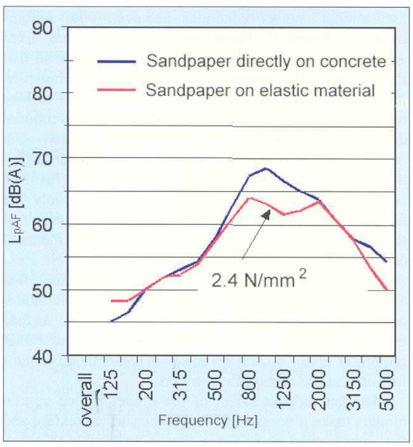

Figure 2.5: Effect of inserting a soft rubber layer between a sandpaper sheet and a cement concrete surface ([6] cited in [7])

2.3 Stiffness effect: hypotheses

Various hypotheses have been suggested to explain possible influence of the road surface stiffness on noise. They basically refer to two phenomena: modification of the excitation level of the tire, radiation of the road surface.

Bennerhult 1979 [1]:

1. "If the impedance of the road surface is of the same order as the impedance of the tire in the relevant frequency range, the road surface will be deflected causing considerable radiated noise".

2. "Noise generated by the impact of the tire and the road (at the forward boundary of the contact patch) will be influenced by the mechanical impedance of the road surface. The importance of this or similar generating mechanisms is not known at present".

Nilsson 1980 [8] :

"At high frequencies[2], tire structure wavelengths tend to become smaller than contact patch dimensions. Excitations at the leading and trailing contact edges must then be treated separately. This means that structural wave propagation within the contact patch itself must be considered too (travelling wave models).
Contact impedance of the tire/road system forms a parameter that would govern such wave transmission. It depends on the road and tire impedances, on the road and tire roughness, and on the elasticity of the road and tire materials. A bald tire with a very smooth road surface results in maximum contact impedance. A tire with small tread blocks on a very rough road surface gives smaller contact impedance. Consequently, in the latter case, tire-wave energy could flow trough the contact patch more easily".

Sandberg 1980 [3]:

1. "The stiffness influences the tire vibrations through the different matching of tire and pavement mechanical impedance (deceleration of the tire tread elements)" [1] [8]

2. "Shock waves in the pavement are produced by the sudden contact between pavement chippings and tire tread elements. These "propagate in the pavement, giving large areas which can radiate sound waves in the air".

2.4 Elastic surfaces

The inclusion of rubber in a mix for wearing course stems from the idea that it would decrease the stiffness of the surface. In his review [9] Sandberg concludes that neither rubber powder mixed with the bitumen nor rubber chips replacing part of the stones in the mix have any significant effect on noise.

However, when rubber is the main ingredient, like with the so-called **poro-elastic**[3] road

[2]The separation between low and high frequencies is 800 Hz - 1000 Hz

[3]von Meier [10] also uses the term *poro-elastic* but for a porous asphalt with a binder added with some rubber. The research addressed acoustic absorption only, not the pavement *elasticity.*

surface experimented in Sweden [11], dramatic vehicle noise reduction can be obtained[4]. Curiously enough, it does not seem that poro-elastic road stiffness was measured.

[4]practical and safety problems remain be solved before the solution can be implemented on a full-scale basis

3 – Introducing the road stiffness in the rolling model

There is thus no doubt that road stiffness influences tire noise. The question is whether soft road surfaces can be practically achieved. Regarding the SILVIA project what will be addressed is the modifications in the interaction phenomena when a tire rolls on an elastic surface and the relative consequences on tire noise.

Only the noise due to tire vibrations will be addressed.

The model

The vibration behavior of the tire belt is characterized by its impulse response $G(x, y, t|x_o, y_o, t_o)$ evaluated in the time domain [12]. Given the external pressure field in the contact zone $F''(x, y, t)$, the displacement of the tire can be obtained

$$z_{tire}(x, y, t) = \int\int\int F''(x_o, y_o, t_o) G(x, y, t|x_o, y_o, t_o) dx_o\, dy_o\, dt_o \tag{3.1}$$

The tire road interaction occurs through the tread gum. In the model, the gum is assumed to be locally reacting with no hysteretic property: it is characterized by its stiffness constant s_g [N/m^3] and can be seen as made of independent springs[1]). The corresponding mechanical impedance[2] is $Z = s/i\omega$.

Rigid road pavement A compression $\Delta h_g(x, y, t) > 0$ of the gum at point (x, y) in the contact zone generates an interaction pressure

$$F''(x, y, t) = s_g \Delta h_g(x, y, t)\, \mathrm{H}(\Delta h_g) \tag{3.2}$$

where $\mathrm{H}(u) = 1$ if $u > 0$, $\mathrm{H}(u) = 0$ otherwise.

Elastic road pavement An elastic pavement can be modelled in various ways:
- semi infinite elastic medium (when rolling on ground for instance)
- multilayer of elastic media
- thin or thick plate on an elastic foundation
- etc.

Depending on the model, bending waves, shear waves, eventually surface waves may occur. In this report a simple model is be used: similar to the tire gum, **the pavement is considered to be locally reacting; it is characterized by its stiffness constant** s_r.

Formally, one can evaluate individually

[1] a representation by an elastic layer has been developed by Larsson [13]
[2] with the convention $x(t) = \int X(\omega) e^{i\omega t} d\omega$

- the deflection Δh_r of the road profile:
  $\Delta h_r \equiv z_{road} - z_{road,o} = -F''/s_r$
- the contact pressure due to the compression of the tire gum between the tire belt and the (deflected) road profile: $F'' = s_g(z_{tire} - z_{road})$,
  which can be written $F'' = s_g[(z_{tire} - z_{road,o}) - (z_{road,o} - z_{road}) = s_g(\Delta h_g - \Delta h_r)$
  where Δh_g is the compression of the tire gum with respect the rigid profile.
- the tire belt deflection (Eq 3.1).

It results from these equations that the contact pressure can also be obtained from

$$F'' = s_{eq}\,\Delta h_g\;\mathrm{H}(\Delta h_g) \tag{3.3}$$

with

$$\frac{1}{s_{eq}} = \frac{1}{s_g} + \frac{1}{s_r} \tag{3.4}$$

The resulting tire belt motion is still evaluated using Eq.3.1.

Rolling with a tire of gum stiffness constant s_g over an elastic road of stiffness constant s_r is the same as rolling with a tire of gum stiffness constant s_{eq} (Eq 3.4) over a rigid road.

This was suggested by Kropp for his model [14]. A parametric study was performed by Wullens [15] on this basis: the study of the influence of the road stiffness amounts to that of the influence of the tire tread gum stiffness.

Exemple Both methods are used in the following exemple:

direct method a tire, with a gum stiffness constant $s_g = 65\mathrm{MN/m}^3$ rolls over a profile of an elastic road with stiffness constant $s_r = 2s_g$,

s_{eq} **method** the tire with a gum stiffness constant $s_{eq} = s_g s_r/(s_g + s_f)$ rolls over the same profile but the road is stiff.

The contact pressure corresponding to a same instant are drawn Fig 3.1 It is verified that

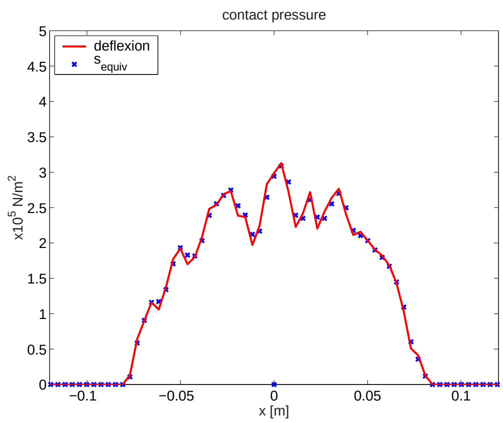

Figure 3.1: Contact pressure obtained by two methods § 3

the numerical estimations corresponding to both methods give the same results (referred respectively as 'deflection' and 's_{equiv}' on the illustration).

4 – Parametric study

The evaluation will be made using the equivalent stiffness method: the tire with a gum stiffness constant s_g rolling on a road profile stiffness constant s_r will be modelled by the tire with a gum stiffness constant $s_g s_r/(s_g + s_r)$ rolling on a rigid road profile.

4.1 Physical values

Evaluations are performed in the time domain. The road profile is taken to be function of the rolling direction only: $z_r \equiv z_r(x)$; the tire rolls on a "washboard" profile. The contact pressure is assumed to be constant over the width b of the contact zone [1].

The values taken for the road and tire gum stiffness do not pretend to correspond to reality: the objective is here to see whether road stiffness may have some influence on tire noise.

- road profile: the road profile is the `a1a1fm` profile from Sperenberg given by BASt.
- gum stiffness: two values are considered for the tire gum stiffness: $s_g = 65\,\mathrm{MN/m^3}$ corresponding to a rather soft gum and $s_g = 200\,\mathrm{MN/m^3}$ corresponding to a rather hard gum [2].
- pavement stiffness: the pavement stiffness values are $s_r = \infty$ and $s_r = n \times s_g$, where $n = 1, 2, 4, 8, 16, 64, 256$.
- rolling speed: 30,50,70,90,110,130,150 km/h.

4.2 The hub force

Loading process

The tire is gradually pressed on the road profile. At each time step the contact forces are evaluated. The loading process is stopped when the resultant of the contact forces (the hub force) balances in a permanent way the nominal loading force (within the required tolerance). The history of the loading process, characterized by the time evolution of the global contact force (the hub force) $F_{tot}(t)$ is drawn Fig 4.1 (Left). The legend $\times 1, \times 2, ...$ correspond to the coefficient n in $s_r = n \times s_g$. The loading process does not appear to depend on the road pavement stiffness.

Rolling process

Once the equilibrium is reached, **the hub position is blocked** and the rolling process started abruptly: the tire velocity is set instantaneously to the nominal speed. The evolution $F_{tot}(t)$ drawn Fig. 4.1 (right) corresponds to several tire rotations.

[1] the width of the contact zone is smaller that the width of the tire

[2] for a 12 mm gum thickness the equivalent Young's modulus would be about $0.78\mathrm{MN/m^2}$ and $2.4\mathrm{MN/m^2}$ respectively

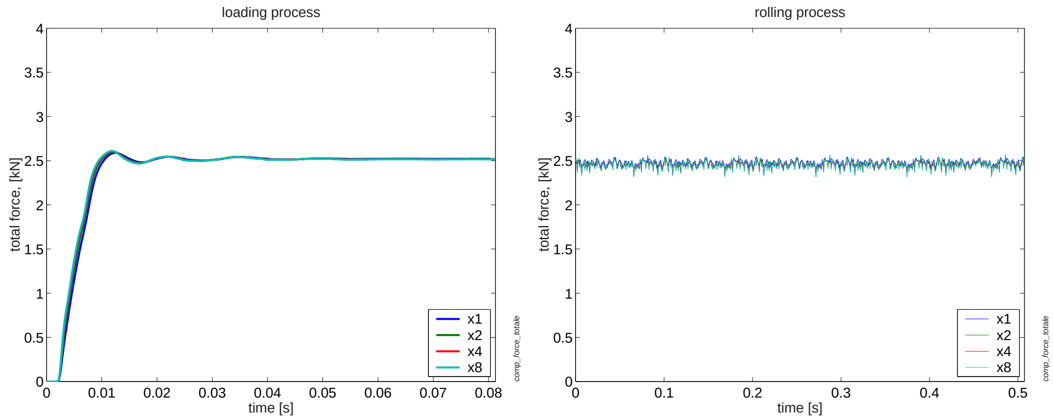

Figure 4.1: Global contact force. Left: loading process- Right: rolling process

The spectrum of $F_{tot}(t)$ changes with the pavement stiffness: the trend is not monotonous in the low frequency range, but above 200 Hz the level tends to decrease when the pavement stiffness decreases (Fig 4.2).

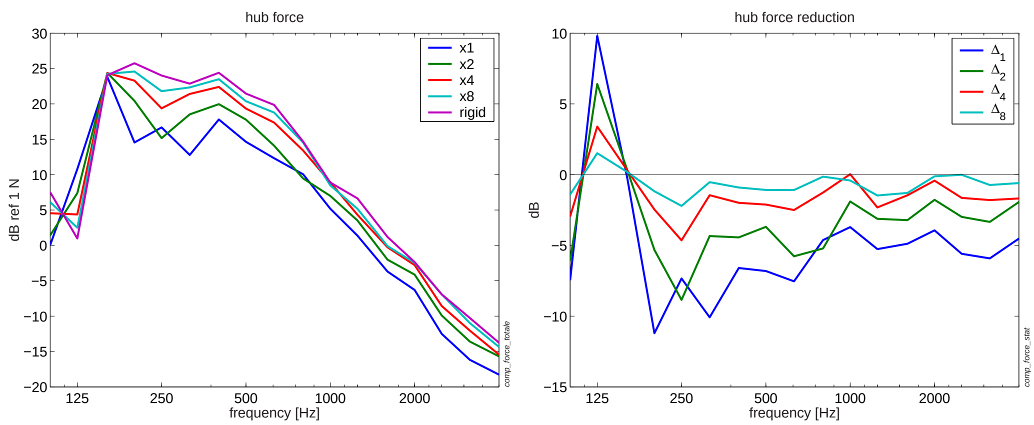

Figure 4.2: Hub force during the rolling process- left: spectrum levels- right: differences wi.r.t. the rigid road case

4.3 The contact pressure

The contact pressure is made of a quasi-static part which maintains the global tire deformation over the contact zone, and a perturbation part due to the profile variations. The results given Fig 4.3 were obtained on the soft pavement ($s_r = s_g$) and on the stiff pavement ($s_r = 8 \times s_g$). The figures read as follows:

- upper part: the tire and road profiles . The continuous line corresponds to the the deformed road profile, the dotted line to the original profile. The vertical scale is the same than the horizontal scale.
- lower part: the contact pressure
- left, soft road case: the road stiffness is equal to the gum stiffness
- right, hard road case: the road stiffness is $\times 8$ times the tire gum stiffness.

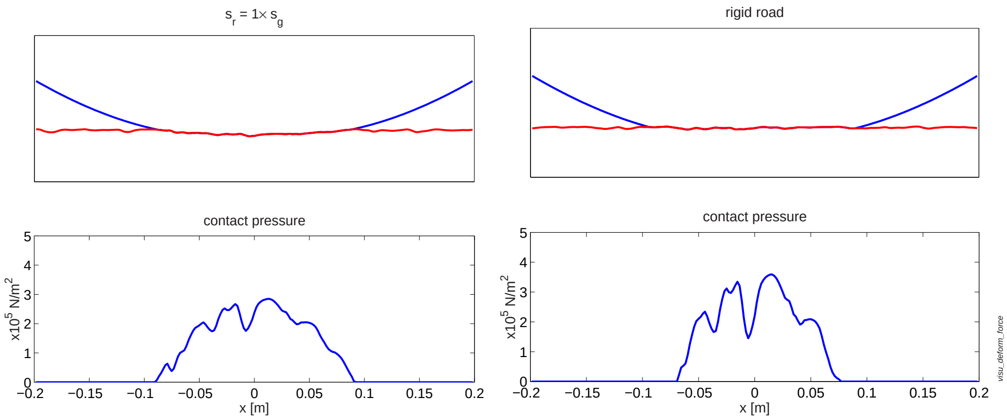

Figure 4.3: Tire and road profiles (upper) and contact pressure (lower) for a soft (left) and a stiff (right) pavement

Due to its rather soft gum, the tire envelopes entirely the road profile: the contact pressure is never null in the contact zone (a zero contact pressure at x would mean that the tire/road contact is lost at x).

One can look at the contact pressure as composed of a quasi static part (corresponding to the tire rolling on a smooth profile) and a perturbation due to the road texture profile [16], [17].

The quasi-static contact pressure

The quasi-static contact pressure is drawn Fig 4.4. When the pavement stiffness decreases, the contact pressure tends to decrease at the center of the contact zone and increase at the entrance and exit. The contact length itself tends to increase.

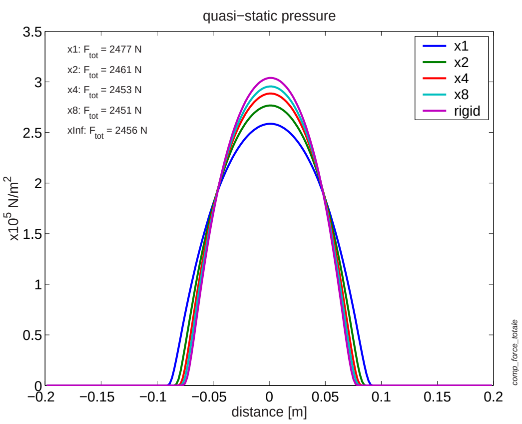

Figure 4.4: contact pressure : quasi-static part

The perturbation contact pressure

The perturbation part of the contact pressure varies with time. The curves drawn Fig 4.3 correspond to two different times. It is seen that the amplitude of the perturbation decreases when the road stiffness decreases.

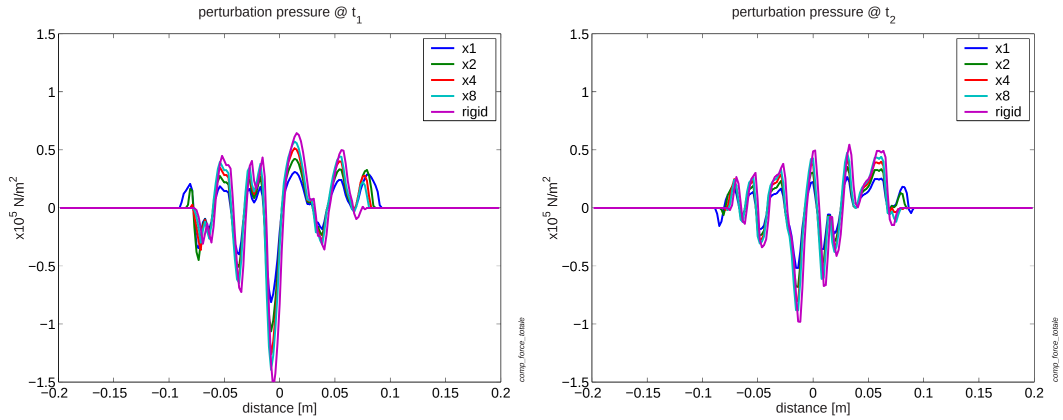

Figure 4.5: contact pressure : perturbation part at two instants

Globally, softening the road decreases slightly the contact pressure amplitude while increasing the length of the contact zone. Rolling on an elastic road reduces the amplitude of the contact pressure perturbations and consequently the rolling noise.

4.4 The radiated noise

The noise evaluations address the vibration noise only. The road surface is acoustically reflective (no absorption). The results are presented in terms of noise power levels (i.e. the whole tire radiation) $L_W(v, s_r, f)$.

The road stiffness influence on the 1/3 octave power noise levels is synthesized on one figure (Fig 4.7) and the global dB(A) level on another (Fig 4.6). The scales are as follows:

horizontal axis the abscissa is the ratio s_g/s_r between the tire gum stiffness and the road stiffness: $s_g/s_r = 0$ corresponds to a rigid road, $s_g/s_r = 1$ corresponds to a road as soft as the tire gum[3].

vertical axis the vertical scale is the reduction $\Delta L_W = L_W(v, s_r, f) - L_W(v, \infty, f)$ obtained with the road of stiffness s_g as compared to the rigid road case: a negative value mean that the non rigid road is quieter than the rigid road.

parameter Each curve corresponds to a given velocity (between 30 and 150 km/h)

Tire-road noise depends on road stiffness inasmuch as the road stiffness constant is of the same order of magnitude than the tire gum stiffness constant. This is clearly expected from the equivalent s_{eq} approach: a change on the tire/road interaction can only occur for a significative change of the contact stiffness[4].

For $s_g/s_r \sim .3$, i.e. for a road about three times stiffer than the tire, the contact stiffness is reduced by 20% only, yet the reduction reaches some 3 dB(A) at 70 km/h (Fig 4.6). When the road becomes as 'soft' as the tire ($s_g/s_r = 1$), the contact stiffness s_{eq} is still half of its initial value s_g, the noise reduction may reach 5 dB(A).

The reduction depends little on speed although it tends to be slightly higher at higher speeds[5] (Fig 4.6).

[3] It seemed reasonable not to consider a road softer than the tire
[4] the evolution of s_{eq}/s_g as function of s_g/s_r is drawn Fig 4.8
[5] The dB(A) reduction at 150 km/h is however the same than the reduction at 50 km/h

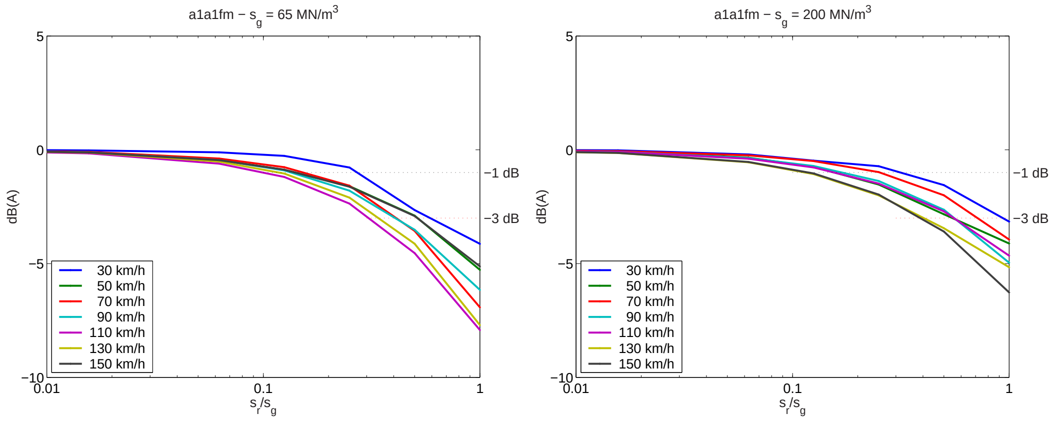

Figure 4.6: $\Delta L_W = L_W(v, \mathbf{s}_r, f) - L_W(v, \infty, f)$ as function of s_g/s_r.
left: $s_g = 65\ \mathrm{MN/m^3}$ - right $s_g = 200\ \mathrm{MN/m^3}$

The reduction is almost null at low frequencies, it gets significant at high frequencies (Fig 4.7).

Power noise spectra Power noise 1/3 octave spectra obtained at 50 km/h and 110 km/h are drawn Fig 4.10. Three spectra are given at each speed corresponding to a rigid road, a road with stiffness constant $s_r = 4s_g$ and a road with $s_r = s_g$. The noise reduction occurs mainly in the mid and high frequency range (also seen in Fig 4.7). This agrees with Wullens results [15] and with the experimental observations of Bennerhult and Beckenbauer (cf above).

Speed law Noise increase with speed appears almost independent of stiffness as can be seen Fig 4.11 & 4.9.

Remark It was realized before concluding the report that despite the high gum stiffness constant $s_g = 200\ \mathrm{MN/m^3}$, the contact between the tire and the profile was 'complete' (Fig 4.12). The conclusions remain to be confirmed for the case of partial contact

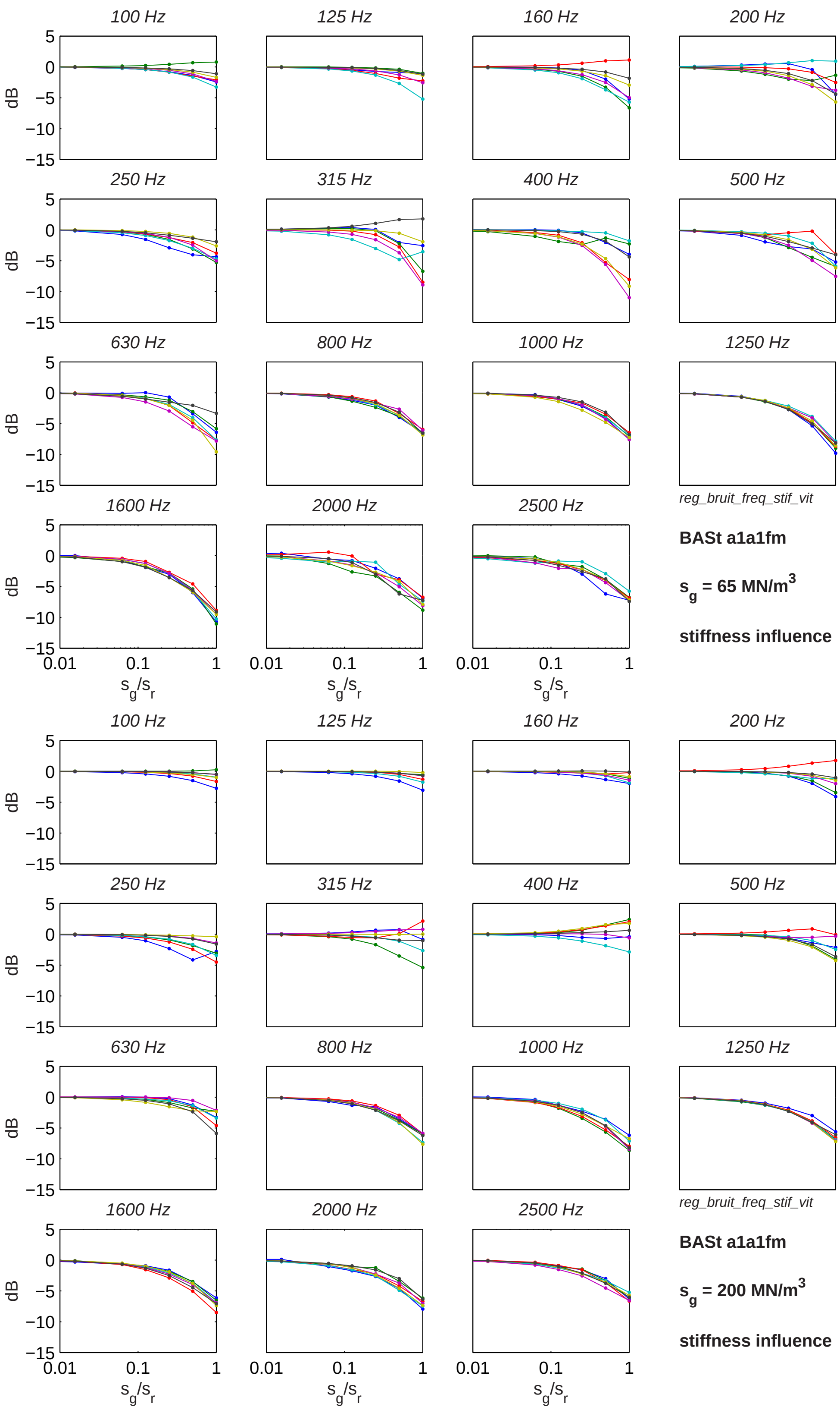

Figure 4.7: $\Delta L_W = L_W(v, \mathrm{s}_r, f) - L_W(v, \infty, f)$ as function of s_g/s_r. The noise levels tend to decrease as the road becomes 'softer'

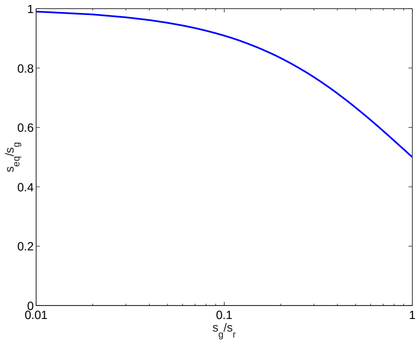

Figure 4.8: evolution of s_{eq}/s_g as function of s_g/s_r

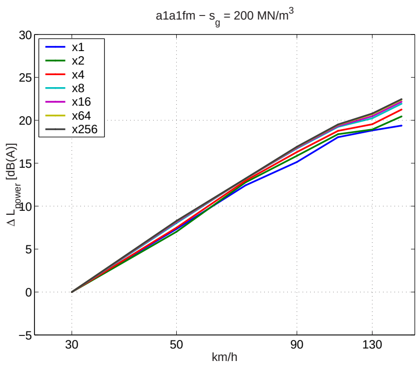

Figure 4.9: $L_W(\mathbf{v}, s_r, f) - L_W(30, s_r, f)$

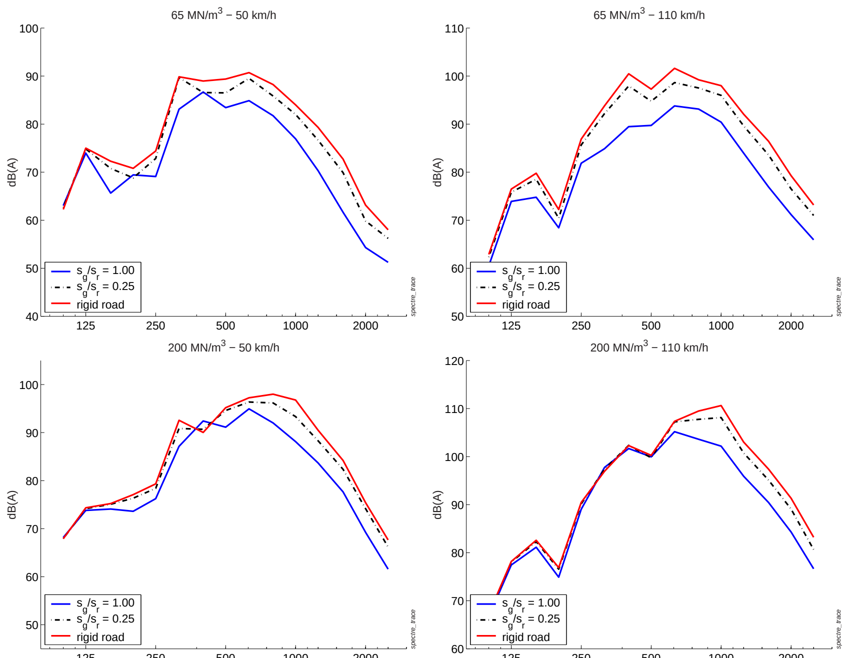

Figure 4.10: Power noise spectrum and road stiffness - left @ 50 km/h - right : @ 110 km/h

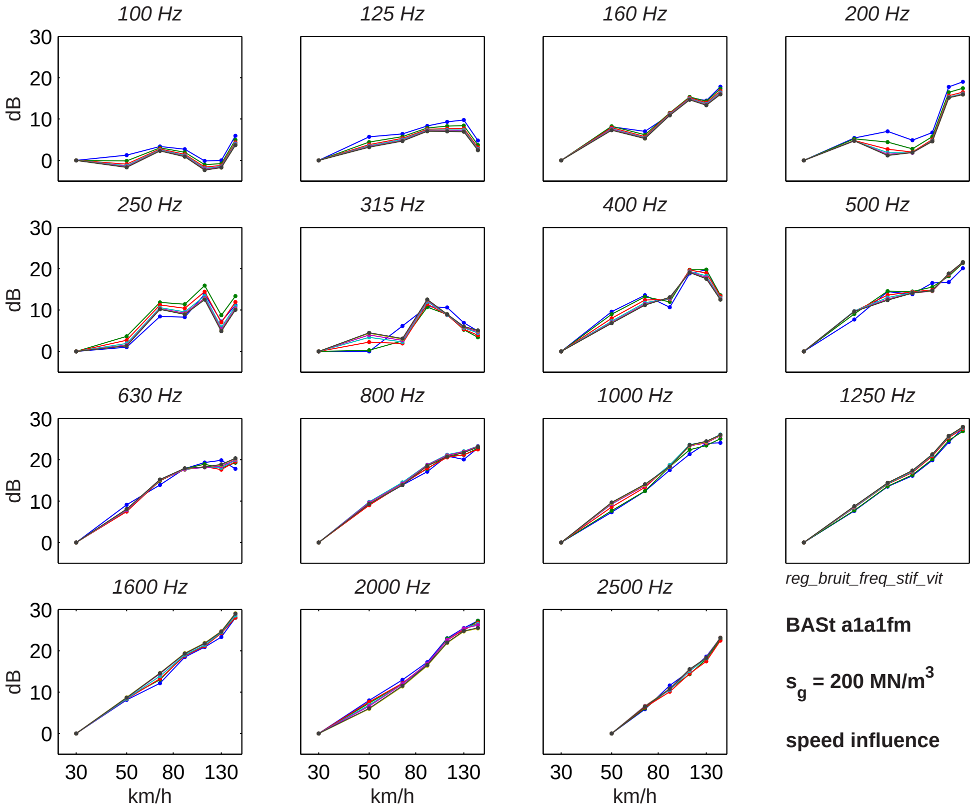

Figure 4.11: $L_W(V, s-r, f) - L_W(30, s_r, f)$

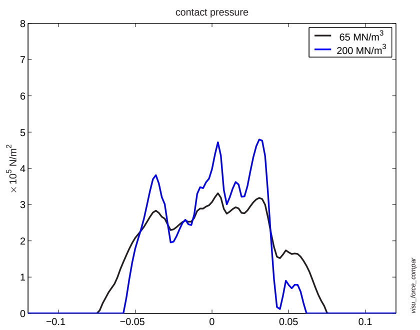

Figure 4.12: Instantaneous contact pressure for $s_g = 65\text{MN/m}^3$ and $s_g = 200\text{MN/m}^3$

5 – Conclusion

The simulation show that vibration induced noise may be reduced if the road stiffness constant is decreased to the same order of magnitude than the tire stiffness constant. The reduction is rather independent of speed and may reach some 5 dB(A). It is significant in the mid and high frequency range.

Although this agrees with experimental observations, it must be recalled that the vibration induced noise addressed here is only part of the tire noise: it is known to contribute mainly in the low and mid frequency range (up to about 1 kHz). According to Wullens [15], decreasing the road stiffness decreases also the air pumping noise. The air pumping modelling used may however not be quite appropriate for quantitative evaluations. Moreover, the air pumping phenomena are known to be strongly affected by vertical or lateral porosity in the contact zone, and this is not yet included in the models.

- There should be no doubt that road stiffness may influence tire noise.
- Road stiffness influences tire noise when the road stiffness constant is less than 10 times the tire gum stiffness constant.
- The stiffness constant, as used in this model, remains to be determined on existing roads.

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