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TIRE-ROAD NOISE : AN ANALYSIS OF THE TIRE VIBRATIONS

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Résumé - Le bruit de contact pneu/chaussée, en partie lié aux vibrations du pneumatique, est une nuisance importante du trafic routier. Nous analysons les vibrations mesurées par un accéléromètre fixé au pneu d'une voiture et leur appliquons des méthodes d'analyse spectrale classique (transformée de Fourier) et d'analyse temps-fréquence (distribution de Wigner-Ville). Nous mettons en évidence deux comportements distincts suivant que l'excitation essentielle provient de la texture de la chaussée ou du dessin de la bande de roulement.

Abstract - Tire vibrations are partly responsible of acoustic nuisance related to tire-road contact noise. We analyse tire vibrations measured by an accelerometer fixed to the tire of a car, both by means of classical spectral analysis (Fourier transform) and by time-frequency analysis (Wigner-Ville distribution). We point out distinct behaviours when the tire is excited by the road texture or by the tire tread pattern.

INTRODUCTION

Noise sources from a rolling vehicle may be classified into two categories : mechanical noise (including engine noise) and rolling noise (or tire/road noise). Whereas mechanical noise has been decreasing since cars are manufactured, tire/road noise has remained stationary /1/. In fact, rolling noise becomes preponderant for most vehicles driving faster than 50 km/h /2/. The resulting acoustic level around main roads has led many countries to focus attention on that form of nuisance.

The tire vibrations are one main acoustic source of rolling noise. The present study is a frequency analysis of tire vibrations, using real experiments of a car equipped with a testing wheel and driving on different types of pavement.

After briefly describing the mechanism of tire vibration generation, we will apply classical spectral analysis to the measured signals, leading to interesting comparisons between the different tire-pavement combinations. Finally, we will show how a more elaborate tool, such as time-frequency analysis, depicts more finely the tire vibration phenomenon.

1 - TIRE-ROAD NOISE : PRODUCTION OF THE VIBRATIONS

The interaction of the road texture and the tire tread pattern results in a deformation of the tire tread (fig. 1). This produces vibrations in the tire carcass around the tire-road contact zone /3/. Vibration waves transmit from each side of the contact zone around the circumference of the tire, where the carcass was proved to be a dispersive and rapidly damped propagation medium /4/. This finally induces vibrations in the tread and sidewall all around the tire, and consequently gives acoustic waves.

We pay no attention here to the question of the radiation from the tire to the air. We rather examine the influence of road texture, tread pattern and car velocity on the frequency characteristics of the resulting sidewall vibrations.

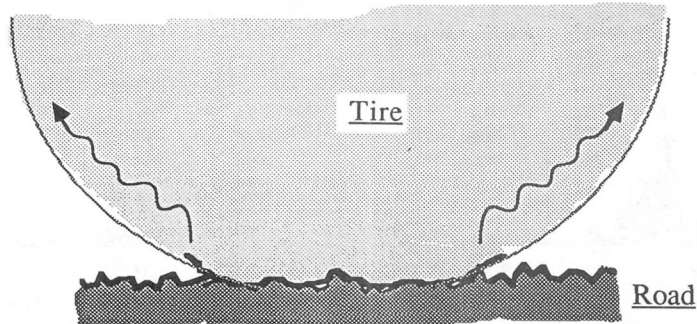


Fig.1 : Generation of tire vibrations

2 - VIBRATION MEASUREMENT : CLASSICAL SPECTRAL ANALYSIS

2.1 - Experiment

An accelerometer is fixed to the sidewall of a test tire of a car driving at constant speed. For homogeneity with other acoustic measurements (pressure measurements taken close to the tire), the acceleration signal is highpass filtered (with cutoff frequency 400 Hz) and A-filtered. Then it is sampled at 20 kHz to be processed by computer.

Two distinct tires were tested :

- a circumferential rib tread pattern tire
- a commercial tire, Michelin MXL 175/70 SR 13

as well as three road textures, classified here by increasing roughness :

- smooth synthetic surface
- bituminous asphalt 0/10
- synthetic surface + aggregate 2/4.

2.2 - Non-stationarity

The vibration signal from the accelerometer is periodic, with period linked to a wheel rotation. In that sense, the measured signal is stationary because infinitely similarly repeated for a constant car speed.

However, regarding the vibration mechanism, the phenomenon is steady in a reference system linked to the tire-road contact zone. But the accelerometer is moving in that system, and scans places with distinct properties :

- the vibration excitation zone near the tire-road contact zone
- two vibration propagation zones, on each side of the contact zone.

The relative movement of the accelerometer to the contact zone implies that the measured signal is affected by variable Doppler coefficients (I don't mention the tire curvature changes around the contact zone, implicitly suppressed by the previous highpass filter).

To illustrate this point, let us consider that the interaction of tire and road in the contact zone generates a vibration at the frequency f_0 , which propagates on both sides of the contact zone. If u is the linear rotation speed of the tire and $c(f_0)$ the wave propagation velocity in rubber, the accelerometer will meet :

- a vibration of frequency $f_0 \left(1 + \frac{u}{c(f_0)} \right)$ amplifying when reaching the contact zone,

- a vibration of frequency $f_0 \left(1 - \frac{u}{c(f_0)} \right)$ getting damped when leaving the contact zone, as the only frequency actually in the tire is $f_0/5$.

In this way, the signal is non-stationary.

2.3 - Mutual influence of tire and road texture

We perform classical FFT analysis on the signals received by the accelerometer for different combinations of the tire and road texture, and for various speeds of the car. There is a general behaviour to an increasing vibration power level as the car speed increases. As for the power distribution with frequency, the spectral analysis led us to distinguish two separate behaviours, depending on the (tire / road texture) combination involved : tire effect preponderance and road texture effect preponderance /5/.

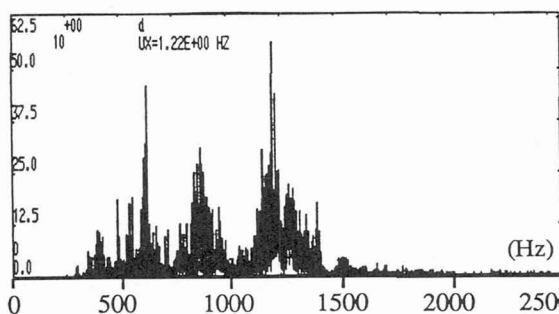


Fig. 2.a : MXL / smooth road texture

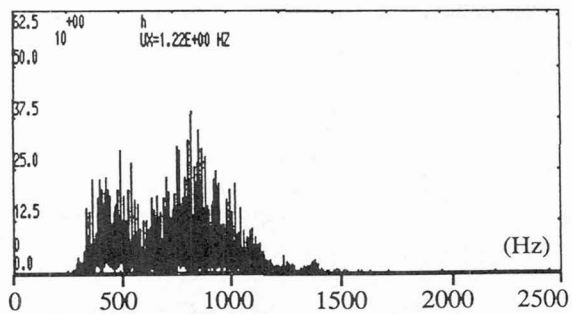


Fig. 2.b : Smooth tire / resin + aggregate

Fig. 2 : Energy spectral density of the tire vibrations, from the rotating accelerometer, at 90 km/h

□ tire effect preponderance : the typical configuration of that class is a grooved tire rolling on a smooth pavement. The excitation essentially relies on the tread pattern. The spectral structure associated is composed of narrowband components, as shown in fig. 2.a for a car driving at 90 km/h. Although commercial tires are designed such that the corresponding spectrum is as flat as possible /6/, it seems in fig. 2.a that there is a basic excitation around 900 Hz (middle peak in the spectrum), which the accelerometer "meets" as 1200 Hz just before it reaches the contact zone, and as a 600 Hz frequency afterwards. As the car speed increases, the general behaviour of this category indicates a global frequency-shift (and scaling) of the spectrum towards higher frequencies. To this class belongs the case (MXL / bitumenous asphalt).

□ road texture effect preponderance : to this class belongs the configuration (circumferential rib tire / resin + aggregate surface), but also the mixed case (grooved tire MXL / resin + aggregate surface). The excitation is essentially due to the road texture roughness. Spectra appear here as wideband spectra (fig. 2.b), independent in position of the speed of the car.

In the context of the first category, involving narrowband signals influenced by the speed of the car, we would like to have a temporal description of the process and show the successive events scanned by the rotating accelerometer. Time-frequency representation techniques offer the opportunity to achieve such a description.

3 - TIME-FREQUENCY ANALYSIS

3.1 - The Wigner-Ville distribution

Time-frequency duality basically prevents from simultaneously describing a temporal and a frequency occurrence of a signal. However, time-frequency representations have been developed to perform the analysis of non-stationary processes. Among these, the Wigner-Ville distribution, performing an energy distribution in the time-frequency plane, is a bilinear representation offering many comfortable properties. These features have been accurately analysed by several authors //1/. We only recall here the classical definition :

$$W_x(t, \nu) = \int_{-\infty}^{+\infty} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-2j\nu\tau} d\tau \quad (1)$$

and mention the implicit occurrence of interference terms due to the bilinear background, practically resolved by introducing two independent smoothing windows, respectively $h(t)$ (frequency smoothing) and $g(t)$ (temporal smoothing). This finally leads to the Pseudo-Wigner-Ville distribution :

$$PW_x(t, \nu) = \int_{-\infty}^{+\infty} |h\left(\frac{\tau}{2}\right)|^2 \left[\int_{-\infty}^{+\infty} g(u-t) x\left(u + \frac{\tau}{2}\right) x^*\left(u - \frac{\tau}{2}\right) du \right] e^{-2j\nu\tau} d\tau \quad (2)$$

$h(t)$ and $g(t)$ respectively define the frequency and temporal resolution of the time-frequency representation.

3.2 - Time-frequency analysis of the tire vibrations

Let us consider the signal received by the accelerometer fixed on the MXL tire and rolling on the smooth road texture at 50 km/h, when passing through the tire-road contact zone. We perform the Pseudo-Wigner-Ville distribution (PWD), which is drawn in fig. 3. The horizontal axis stands for the frequency axis (from 0 to 2500 Hz), and the vertical axis stands for the time axis (for a 65 ms duration). The logarithmic PWD level is represented by a colour scale. The marginal figure (fig. 3 left) shows the temporal signal.

As the accelerometer approaches the tire-road contact zone, we see the main component ① oscillating from approximately 500 to 700 Hz and stopping at the entrance of the contact zone. Simultaneously, ② is the first harmonic of component ①. Then, there is a short wideband component ③ at the output of the contact zone. ④ is the dopplerized component when the accelerometer leaves the contact zone (highpassed with cutoff frequency 400 Hz) and ⑤ its first harmonic.

This figure confirms the presence of a narrow-band component, dopplerized before and after the contact zone. However a component similar to ① remains after the contact zone, which we cannot explain yet. The main point of this figure concerns the oscillation of component ①, which can be attributed to the tread pattern.

CONCLUSION

Classical spectral analysis and time-frequency analysis of the tire vibrations led us to point out two distinct spectral behaviour, depending on whether the excitation is essentially due to the tire tread pattern or to the road texture roughness. The basic handicap of the present experiment is linked to the non-stationarity introduced by the rotating accelerometer. Further investigations should then involve vibration measurements through a laser transducer pointing at the tire. This would lead to a stationary signal, but spatially punctual.

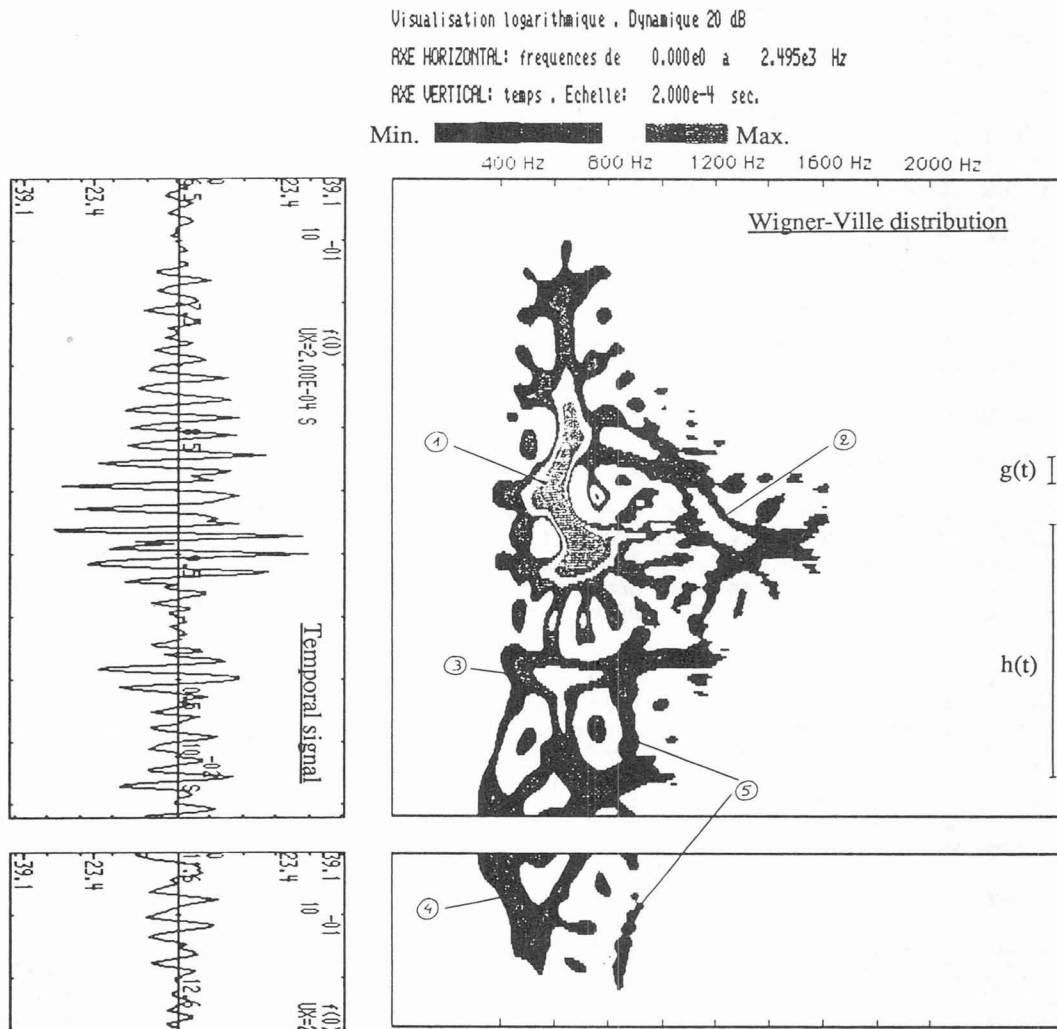


Fig. 3 : Wigner-Ville distribution of the tire vibrations, in the case (MXL / smooth road texture) at 50 km/h

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