CORRELATIONS BETWEEN TIME-FREQUENCY SPECTRAL CHARACTERISTICS AND PSYCHOACOUSTIC METRICS

PACS REFERENCE: 43.60.c

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ABSTRACT

A novel approach to the widespread problem of evaluating the noise quality of a car engine is presented. Traditionally some psychoacoustic metrics of the sound are calculated and used to generate a certain Noise Quality Index (NQI) according to a previous jury assessment. In this paper we relate well-known psychoacoustic metrics - which usually contribute to generate the NQI - to time-frequency characteristics of car noise, in order to find relations between both kinds of parameters. These relations could help engine designers to predict the noise quality just analysing the spectral changes of the noise waveform. Some promising results are showed.

1. INTRODUCTION

Sound quality is a term describing an objective measure of the subjective perception to a radiated sound. Knowledge about how people perceive sounds has been applied to engine noise, and more precisely, to engine idling noise (see for example [1-3]), since this noise can have a considerable influence on potential buyers. Nevertheless, to quantify how the individual signal attributes are perceived and combined to give a listener an overall impression of engine noise is still a difficult task.

On the other hand, time-frequency (TF) techniques as Wavelets and Wigner-Ville transformation have also been applied to analyse and study the combustion process of different kinds of engines [4-6], showing that TF analysis represents a powerful tool in order to help engine designers to understand the combustion process, which is supposed to be the main source of engine noise.

Concerning our problem of noise quality evaluation, usually a wide set of different metrics of the signal are calculated, involving from psychoacoustic features to statistical and spectral parameters [3]. Once the engine noise has been evaluated by a jury and an assessment of the signals has been obtained, the calculated metrics are compared to it. Those metrics showing sufficient correlation with the results of the jury test are selected in order to build an objective measure of the annoyance caused by the engine [2,4]. Some examples of typical metrics used in engine noise are: ISO532B loudness, sharpness, fluctuation strength, roughness,

[1] This work has been supported by CICYT grants TIC1999-0444-C02-01 and TIC2000-1683-C03-01.

impulsiveness, rumble noise and different ratios between half-order harmonics, third-order harmonics, etc.

The objective of this work is to search for relations between the most common psychoacoustic features - loudness, sharpness, fluctuation strength and roughness - and some signal characteristics extracted from time-frequency (TF) analysis. This way, we will try to explore new metrics to improve the objective evaluation of subjective perception, and we will also be able to identify how changes in signal spectrum are perturbing related psychoacoustic features. Section 2 describes the time-frequency analysis carried out and the parameters extracted from it. Section 3 details the experimental settings together with a discussion of some interesting results, whereas conclusions are explained in section 4.

2. TIME-FREQUENCY ANALYSIS

Noise signals from a High-Speed Direct Injection car diesel engine were recorded at 48000 samples per second (more details about the experiment are given in the next section).

2.1. Time-frequency processing

The following time-frequency processing was carried out: signal spectra was divided in four different frequency bands covering the human audible range (from 20 Hz to 16 KHz). Firstly, signals were demodulated to an appropriate frequency in order to translate the band of interest to base-band. Secondly, demodulated signals were decimated by a suitable factor and then modulated again to adjust the band of interest to the whole range of the normalized spectrum. Finally, the Short-Time Fourier Transform (STFT) was calculated for every signal.

Afterwards sixteen parameters were extracted from the STFT, the same four ones in each band: the average and standard deviation of the energy, and the average and the standard deviation of the instantaneous frequency, whose expression is given by:

$$f(t) = \frac{1}{2p} \frac{\int_{-\infty}^{\infty} w STFT(w,t) dw}{\int_{-\infty}^{\infty} STFT(w,t) dw} \qquad (1)$$

2.2. Criteria for the selection of the bands

As it has been noted, the whole spectrum was partitioned in four bands, whose respective initial and final frequencies are given in table 1, together with the respective range occupied in the Bark scale:

	1st Band	*2nd Band*	*3rd Band*	*4th Band*
f_initial (Hz)	20	500	1700	4600
f_final (Hz)	625	1750	4825	15600
Bark range	*[1,6]*	*[5,12.8]*	*[12.6,19]*	*[18.7,23.2]*

Table 1. Initial and final frequencies of the bands whose STFT has been calculated, and respective range occupied in the Bark scale

The partition is not arbitrary, but it has been chosen in order to separate four different behaviours experimented by the stationary loudness spectra of the noise which are related to the marks achieved in the jury test by each sound. These variations can be observed as an example in figure 1: it shows the stationary loudness of several noises recorded at 3000 r.p.m. In the loudness spectrum the second and third band are related with the subjective mark just by a direct way: high loudness cause a bad mark, whereas low levels of loudness give rise to the best marks. On the other hand, changes of the first band do not seem to have any influence on the subjective sensation, and the last band has very little content to be considered a priori. Same effects experiment the stationary loudness spectrum of noises recorded from the engine rotating at high speed, whereas for low r.p.m. levels (900 to 1500), only the second band was related to the jury mark by the same direct way.

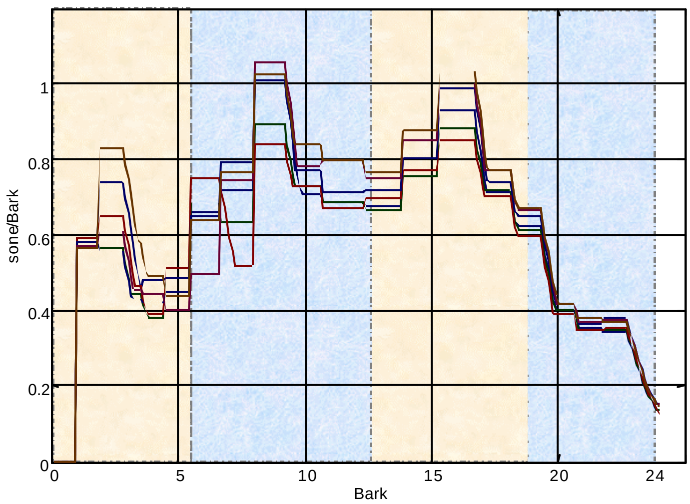

Figure 1. Stationary loudness of several noises recorded at 3000 r.p.m.

3. EXPERIMENTAL SETTINGS AND RESULTS

The experiment involved a commercial high-standing car diesel engine. Noise signals were recorded by a binaural head and torso simulator (Head Acoustics) that was positioned one meter in front of the engine. Both mannequin and engine were inside an anechoic chamber. Recordings were made for eight different engine r.p.m.s: 900 (considered as idling noise), 1500, 2000, 2500, 3000, 3250, 3500 and 4000, and several combustion parameters were changed for each r.p.m. For example, different charge injection volumes were used, rail pressure was increased or decreased in respect of the nominal pressure, charge injection degree was also moved forward or backward within a range of 20º, etc. Altogether 81 different noise signals were recorded.

We have calculated the loudness [7], sharpness (according to Zwicker [8] and Aures [9] definitions), roughness, fluctuation strength and time-frequency parameters described in section 2 for each noise signal. Comparisons between psychoacoustic features and jury assessments, TF parameters and jury assessments, and also between both psychoacoustic features and TF parameters were carried out in order to detect relations or similar behaviors. Due to the limited extension of this paper, we will discuss only the results obtained for two groups of diesel noise: Low r.p.m.s (18 signals at 900 and 1500 r.p.m.) and High r.p.m.s (24 signals at 3000 r.p.m.).

3.1. Low r.p.m.s

The estimated Noise Quality Index (NQI) for this kind of noise is expressed as a multiple regression of some psychoacoustic and statistic parameters:

$$NQI = 12.59 - 1.71*Kurt - 1.23*L - 2.48*FS + 7.85*Skew + 9.41*SharpZ \qquad (2)$$

where *Kurt* and *Skew* stand for the kurtosis and skewness of the time signal respectively, *L* means the loudness, *FS* the fluctuation strength and *SharpZ* the sharpness calculated by Zwicker method.

Figure 2 shows the above NQI versus jury assessment. The multiple linear regression model performed has an R^2 statistic of 86.7% which indicates that the model as fitted explains the 86.7% of the variability of the jury score.

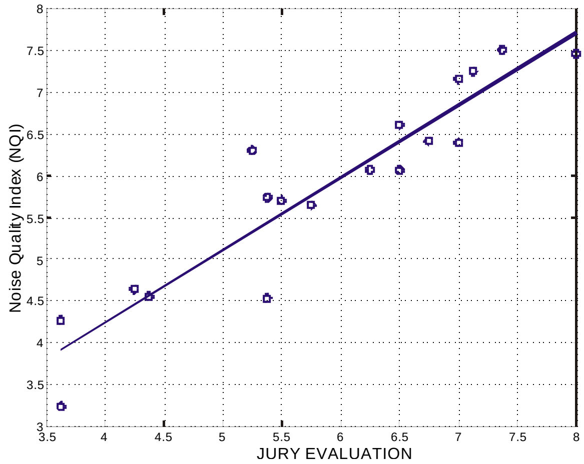

Figure 2. Noise Quality Index versus jury assessment for low r.p.m. signals.

From the above expression of the NQI, it can be noticed that loudness, sharpness (according to Zwicker method) and fluctuation strength contribute significantly to the perceived noise quality. How do these features relate to time-frequency parameters? Table 2 shows the relationships between TF and psychoacoustic parameters so every psychoacoustic feature may be expressed by a multiple linear regression model of the TF parameters marked with a cross. Moreover, the R^2 statistics of each multiple regression fitting is showed at the last row.

	Loudness	*Sharpness(Z)*	*Sharpness(A)*	*Roughness*	*Fluct. Str.*
E_1	X				
E_2		X			
E_3	X	X			
E_4			X	X	X
s_{E4}				X	X
FI_1				X	X
FI_3		X			
FI_4		X	X	X	X
R^2	98%	98%	96.4%	93.3%	93.3%

Table 2. Relation between psychoacoustic features and time-frequency parameters for low r.p.m. signals. E_i stands for average energy of i-th band, s_{E4} is the standard deviation of energy in the 4th band, whereas FI_i means average instantaneous frequency of i-th band.

As it can be seen from table 2, the 98% of the variability of loudness depends only on the average energies of bands 1 and 3. This may be a surprising result since most of the spectral power of low r.p.m. signals stands below 4 KHz. Consequently, energy of band 2 (see table 1) should also contribute to the perceived loudness, however this is not the case.

Concerning sharpness model, differences between Zwicker and Aures methods have been found. Aures sharpness only depends on the TF parameters of the highest frequency band (over 4.6 KHz), whereas Zwicker model is related to medium band energies and instantaneous frequencies of highest bands. These differences may be explained by the fact that Aures model weights the loudness spectrum in such a way that enhances high frequencies and attenuates low frequencies respect to the weighting function applied by Zwicker model.

Respect to roughness and fluctuation strength relations, their R^2 statistics are the lowest ones, and they need more parameters to describe their behaviour than loudness or sharpness. Taking into account that roughness and fluctuation strength intend to represent the perceived sensation of very low frequency (or amplitude) modulation, their relation to the TF parameters is not really evident.

Finally, it should be noticed that sharpness model has a very good fitting in table 2. However another interesting conclusion can be stated from comparison between predicted and real sharpness values, which is showed in figure 3. Four noise signals appear clearly separated from the remaining ones. Sharpness values of these four signals are distinctly greater. These four signals were originated increasing the injected volume of diesel from 12 to 42 mm^3 for each cylinder and cycle. Therefore it can be stated that increasing the charge injection volume involves increasing the perceived sharpness of the engine noise.

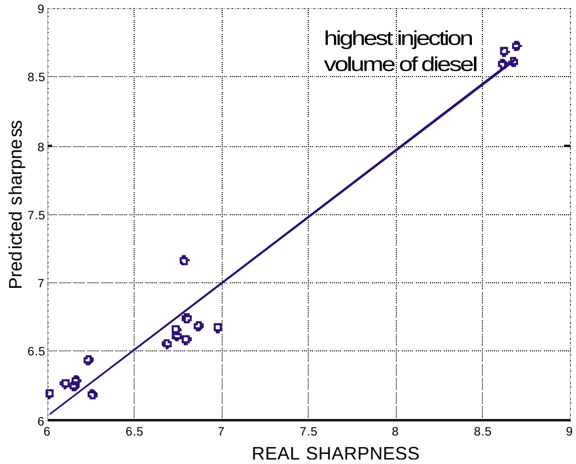

Figure 3. Predicted sharpness versus real sharpness for low r.p.m. signals.

<u>3.2. High r.p.m.s</u>

Table 3 shows the relationships between TF and psychoacoustic parameters for high r.p.m. noise signals. In this case, an adequate model to relate roughness and fluctuation strength to TF parameters does not seem to exist (result for fluctuation strength is not showed since it is analogous to roughness model). This conclusion reinforces the hypothesis that the specific TF parameters selected in this experiment are not enough significant to explain low-frequency modulation effects.

	Loudness	*Sharpness(Z)*	*Sharpness(A)*	*Roughness*
E_1	X	X		
E_2	X			X
E_3	X		X	X
E_4		X	X	
FI_1		X		
FI_3		X	X	X
FI_4		X	X	
R^2	98.7%	88%	97.6%	61.6%

Table 3. Relation between psychoacoustic features and time-frequency parameters for high r.p.m. signals.

On the other hand, loudness and sharpness keep the same relationships observed for low r.p.m. signals: average energies of the bands below 5 KHz completely describe loudness variability, whereas sharpness is related to average energy and instantaneous frequency of high and medium-high frequency bands.

Respect to the rise of sharpness values when the injected volume of diesel increases, this effect is also visible in high r.p.m. signals (see figure 4), although it is not as evident as in the low r.p.m. case.

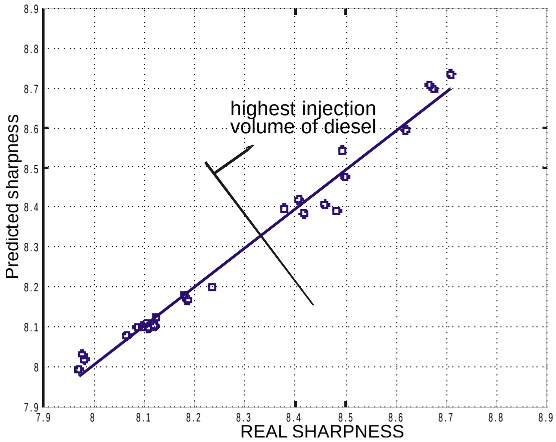

Figure 4. Predicted sharpness versus real sharpness for high r.p.m. signals.

4. CONCLUSIONS

In this paper we have obtained meaningful and reliable relations between some of the well-known psychoacoustic attributes (loudness and sharpness) and specific spectral characteristics of diesel engine noise.

Those spectral features are widely used by automobile engineers to help them to relate the combustion process carried out inside the cylinders to the Sound Pressure Level (SPL) radiated by the engine. From this point of view, the dependence on several TF parameters that loudness and sharpness show can supply an extra knowledge about the perceived sensation of engine noise quality.

REFERENCES

[1] R. Ingham, N. Otto, T. McCollum, *Sound Quality Metric for Diesel Engines*, Proc. Noise and Vibration Conference SAE 1999-01-1819,1999.

[2] K. Shafiqussaman, O. Johansson, W. Lindberg and U. Sundback, *Development of an Annoyance Index for Heavy-duty Engine Noise using Multivariate Analysis*, Noise Control Eng. J., **45**,(4), pp. 157-167, 1997.

[3] M. de Diego, A. González, G. Piñero, M. Ferrer and J.J. García-Bonito, *Subjective Evaluation of Actively Controlled Interior Car Noise*, Proc. of Int. Conf. Acoustics, Speech and Signal Processing (ICASSP 2001), **5**, pp. 1909-1912, 2001.

[4] B. Samimy and G. Rizzoni, *Mechanical Signature Analysis using Time-Frequency Signal Processing: Application to Internal Combustion Engine Knock Detection*, Proceedings of the IEEE, **84**, pp. 1330-1343, 1996.

[5] L. Stankovic, J.F. Böhme, *Time-Frequency Analysis of Multiple Resonances in Combustion Engine Signals*, Signal Processing, **79**,(1), pp.15-28, 1999.

[6] Y. Ren, R.B. Randall and B.E. Milton, *Influence of the Resonance Frequency on the Control of Knock in Diesel Engines*, Proc. of the Institution of Mechanical Engineers Part D - Journal of Automobile Engineering, **213**, pp. 127-133, 1999.

[7] ISO 532B, *Acoustics - Method for Calculating Loudness Level*, 1975.

[8] E. Zwicker, H. Fastl, *Psychoacoustics. Facts and models*, Springer Verlag, 1999.

[9] G. Von Bismarck, *Sharpness as an Attribute of the Timbre of Steady Sounds*, Acustica, **30**, pp. 159-172, 1974.