Diesel knock noise from combustion phenomenon to perceived signals

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Combustion noise still remains a major concern when designing engines for vehicles passenger comfort. Among most efficient strategies for reducing Diesel knock are modifications of engine parameters used for controlling combustion processes. This work aims at giving guidelines when controlling these processes to improve customers combustion noise perception. A methodology is described, which establish a relation between the engine tuning parameters, directly linked to cylinder pressure evolutions, and their effects on perception. We use cyclic Wiener filters allowing realistic overall Diesel noise re-synthesises from cylinder pressure signals. Cylinder pressures are split into elementary components, leading to different types (and patterns) of physically admissible modifications. A perceptive test is then conducted to establish a perceptive space of Diesel combustion noise based on some different pressure cylinder noticeable patterns. An issue is a better understanding of the subjective effects, particularly rhythmic ones, produced by such pulse trains.

Introduction: Perceived effects of combustion noise and mechanical models

The work leading to this paper is both a perceptive study of impact sounds and an experimental, mechanical, investigation of Diesel engine vibro-acoustic properties, throught its noticeable combustion noise (also called ”Diesel knock”). Combustion noise generated by Diesel engines is (still) a major concern for several types of automotive engineers – and final clients, which explains the large number of existing publications dealing with this particular topic (references [7, 3] are then two among many other ones).

One important issue is to establish significant and understandable relations between the parameters used to control the engine, particularly those conditionning the fuel injection process in cylinders, and an evaluation of the combustion noise as perceived by clients inside (and outside) their car. We then need hearing evaluations, that implies audible realistic sounds[1], and control of the corresponding combustion control parameters, that implies explicit knowledge of (causal) transfer functions between combustion processes and combustion noise.

Part 1 will remind some major items about Diesel combustion noise and present the physical model we use for the engine cylinder pressures. Part 2 is dedicated to the construction of transfer functions *via* Wiener filters, representing the complex motor mechanisms. Part 3 describes the perceptive test setup, including the process used for generating various kinds of engine sounds. Part 4 gives some information about test results and their interpretation.

1 Physical origins and observation of combustion noise

We call combustion noise the part of the noise produced by the operating Diesel engine which is caused by the combustion process taking place into the cylinders. The major underlying phenomenon producing this noise is the very fast rise up of pressure in the different cylinders, which characterizes the compression-ignition Diesel combustion process.

[1] In order to simplify the problem, but moreover to be able to characterize an engine and not a (vehicule,engine) pair, we only considered in this work recordings made in an anechoic motor test bench.

Combusion noise then strongly depends on the thermodynamic conditions when operating: Diesel knocking noise is for instance typical when starting cold engines [7].

Seen as a whole thermodynamic machine an engine is a quite complex system to model and observe. For our vibroacoustic purpose we consider that the in-cylinder pressures temporal derivatives characterize the physical sources of combustion noise. The transfer functions we will use then link in-cylinder pressure derivatives and acoustic pressures, both considered as time-varying functions and known on the duration needed for the audio synthesis[2]. Both of them are measurable *via* sensors in an engine test bench. Figure 1 shows an elementary temporal derivation of one in-cylinder pressure, with a temporal window centered on the auto-ignition process.

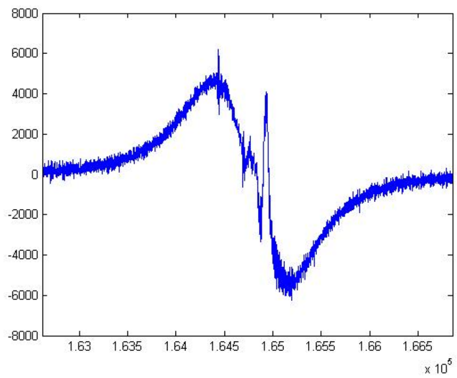

Figure 1: Example of one temporal derivation of in-cylinder pressure signal, focused near the auto-ignition process.

An objective is to simulate different cylinder pressure evolutions and apply to them mechanical transfer functions, in order to generate – and listen to various combustion noises. Starting from a few measured ones on a real operating engine, we need to create a generic model for a cylinder pressure derivative evolution, using parameters directly linked to the physical events producing Diesel knock *and* directly linked to the control parameters monitoring engineers use in practice to set up the global combustion process. We here suppose fixed engine rotation speed and load.

[2] It is important to realize that the overall mean or maximum value, and even mean values of cylinder pressures on the four stroke cycle give not a sufficient information for building realistic Diesel engine sounds.

On Figure 1 we can distinguish several components each corresponding to a physical phenomenon occuring during one (four stroke) engine cycle. The first component is the global, low frequency evolution of the derivative, which is mainly due to the pure compression cycle occuring in the cylinder. This component will not be modified in the following work, as this compression cycle is not supposed to vary from one combustion setup to another (for a fixed speed and load). Figure 2 shows this compression component and the residual part. The second component is the sudden rise of pressure located near the top death center, due to main combustion process when most of the fuel load is injected into the cylinder. A third remarkable component we will separate is a preceding peak in the pressure derivative, due to pilot fuel injection and consecutive auto-ignition process. Depending on operating conditions and combustion strategies retained, no pilot injection or several ones have to be considered.

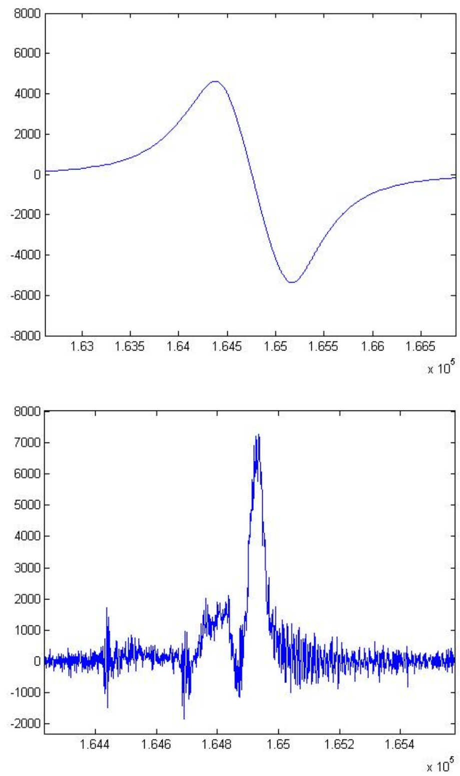

Figure 2: Compression component (top) and residual part (bottom) of the elementary cylinder pressure derivative.

In a first time different signal processing tools, empirical modal decompositions (EMD) for instance, are used together to separate these N_k components of a real measured pressure derivative as expressed in Eq. (1), where $P_{\text{cyl }i,n}$ represents the total pressure measured in cylinder i over the $[t_{n-1}\ t_n]$ temporal window corresponding to the n^{th} engine cycle.

$$\frac{\mathrm{d}P_{\text{cyl }i,n}}{\mathrm{d}t}(t) = \sum_{k=1}^{N_k} C^k_{\text{cyl }i,n}(t) \qquad t \in [t_{n-1}\ t_n] \tag{1}$$

In a second time modifications are operated on these components in order to produce re-synthetized pressure derivative signals (see Eq. (2)) and finally new, modified combustion noise signals. Modifications $\mathcal{T}^k_i$ are specific to each components and cylinders but are the same for all the four stroke cycles indicated by the n subscript.

$$\left(\frac{\mathrm{d}P_{\text{cyl }i,n}}{\mathrm{d}t}\right)^{\text{mod}}(t) = \sum_{k=1}^{N_k} \mathcal{T}^k_i\Big(C^k_{\text{cyl }i,n}\Big)(t) \qquad t \in [t_{n-1}\ t_n] \tag{2}$$

For a N_c four stroke cycles length recording, the entire signals are obtained by concatenations of the N_c elementary signals defined on each cycle, corresponding to the $[t_{n-1}\ t_n]$ temporal intervals. The next step is to apply on pressure derivatives adequate filters $\mathcal{H}_i$ leading to the "best" approximation of the related combustion noise $\tilde{p}^{\text{comb}}$ as expressed in Eq. (3).

$$\tilde{p}^{\text{comb}}_n = \sum_{i=1}^{4} \tilde{p}^{\text{comb}}_{i,n} = \sum_{i=1}^{4} \frac{\mathrm{d}P_{\text{cyl }i,n}}{\mathrm{d}t} * \mathcal{H}_i \tag{3}$$

The construction of $\mathcal{H}_i$ is detailled in the next section.

2 Evaluating physical transfer functions using referenced Wiener filtering and cyclo-stationary theory

A major difficulty is the practical estimation of the mechanical transfer functions linking cylinder pressure derivatives and combustion noise radiated by the engine structure[3]. Two points to be highlitghted are, firstly, the complexity of the engine structure and mechanisms and, secondly, the precision required to deal with realistic audio synthesis. Finite element models are usefull for many conception steps in the mechanical design of engines, but are not yet relevant to simulate the temporal acoustic pressures we need for perceptive studies on Diesel knock. We use so experimental approaches and data recorded on existing Diesel engines to determine the $\mathcal{H}_i$ transfer functions. For this study we used experimental data recorded on a PSA 1,6 l HDi, four cylinders engine block, with in-cylinder and acoustic pressures both recorded in time domain, at high frequency sampling (above 50 kHz) allowing audio processing. All recorded signals are filtered between 200 or 400 Hz and 7000 Hz, where combustion noise is supposed to be audible.

Another major difficulty comes with the specific case of combustion noise, which is one component among many others in the overall engine noise p recordable with microphones in a test bench (see Eq. (4)): the remaining part p^{res} contains various noises which are not physically caused by the combustion process[4].

$$p = p^{\text{comb}} + p^{\text{res}} \tag{4}$$

[3] We suppose that, for given engine speed and load, a linear transfer is a valid approximation.

[4] Some examples are injector, timing belt, turbo noises, ... which can not be cancelled without cancelling or strongly modifying combustion noise.

Then, specific transfer estimators have to be constructed in order to evaluate the $\mathcal{H}_i$ filters and the resulting approximations of combustion noise $\tilde{p}_i^{\text{comb}}$. This operation can be seen either as a denoising of p or an extraction of p^{comb}.

Extracting the combustion noise temporal signal from the overall engine noise is not a trivial task because these signals are complex and, particularly, instationary. However different works done by Antoni [1] and more recently Pruvost [6], among other contributors, adressed successfully this problem using a generalization of referenced Wiener filtering. Angular (re)synchronization procedures and cyclostationary process theory are used to define referenced cyclic Wiener filters $\mathcal{W}_i$, whose estimation gives a very good approximation for each $\mathcal{H}_i$. The procedure uses the in-cylinder pressures (derivatives) as reference signals for the combustion process and suppose that other sources producing the residual noise p^{res} are not correlated with them.

Wiener filters are built and applied in the frequency domain, using cyclic auto- and cross-powerspectrum estimators (see Eq. (5)). Some particular requirements are necessary during data recording, as a key point is the management of both time/frequency and angular/order domains.

$$\hat{\mathcal{H}}_i\,(f) \approx \hat{\mathcal{W}}_i\,(f) = \frac{S_{\dot{p}_{\text{cyl}\,i}\,p}\,(f)}{S_{\dot{p}_{\text{cyl}\,i}\,\dot{p}_{\text{cyl}\,i}}\,(f)} \tag{5}$$

As the precise construction of these particular Wiener filters and the corresponding algorithms to implement are not the main topic of this paper, we will not detail further this part and we will focus on the use of these evaluations of the $\mathcal{H}_i$ transfers to adress the problem of perceptive evaluation of combustion noise linked with combustion control parameters.

More information, particularly on the important theoretical background and cyclostationarity, is for instance given in references [1, 6].

3 Perceptive tests using physically modified Diesel engine sounds

Physical models and signal processing tools presented in parts 1 and 2 will be used to generate various modified Diesel engine sounds and then characterize the perceptive effects linked with the physical modifications we have chosen. A goal is the description of a perceptual map and a quality scaling proposition for a better understanding of these pulse trains perception and of the perceptive influence of combustion parameters we have modified.

3.1 Construction of modified engine sounds

At this point we suppose to have one recording on our real 1,6 l HDi engine, operating at fixed speed (1500 rpm) and load (6 bar). Data aquisitions start with a four stroke cycle ($t_0 = 0$) and end with the last $N_c{}^{\text{th}}$ cycle, at time t_{N_c}. Signals are recorded during, typically, a few seconds. Using the methodology described in part 2 we identify for this particular operating point the four $\mathcal{H}_i$ transfer functions. Once the separation between combustion and residual noise signals is achieved as expressed in Eq. (4), various modified realistic engine Diesel sounds are obtained following this way :

- residual engine noise p^{res} is separated from p
- for each cycle and cylinder, pressure derivatives are computed and split into N_k components
- for each cycle and cylinder, $\mathcal{T}_i^k$ modifications are applied on these components
- for each cycle and cylinder, the N_k modified components are summed and $\mathcal{H}_i$ filters are applied to build the resulting modified combustion noise signals
- modified combustion noise signals are summed over the four cylinders and concatenated over the N_c cycles, leading to the new modified overall combustion noise
- original residual noise p^{res} is then added to the modified combustion noise to produce the final modified engine noise, used for perceptive tests.

A key point [4] ensuring the realism of re-synthetized Diesel engine noises is that both the specific acoustic signatures of cylinders and the cycle to cycle variations of combustion sources and noise are kept.

3.2 Stimuli

For this study, different types of $\mathcal{T}_i^k$ transformations have been used. Their design process, firstly, equilize the different maximum in-cylinder combustion pressure between cylinders. Secondly, these modifications are designed to apply different gains (for instance) on combustion cylinder pressure derivatives. As an example, described in Figure 3, gain modifications can produce different patterns, leading to different rhythmic sensorial experiences. Modifications can be identical for all cylinders (case "a") or can strengthen amplitude differences in combustion pressure derivatives between cylinders (cases "b", "c", "d" and "e"). Considering pattern "a" and modifications on the pilot combustion cylinder pressure derivative only is a mean to study the overall psychoacoustic effect of pilot strategies, widely used in HDi control systems. Considering other patterns "b" to "e" is a mean to focus on rhythmic effects resulting from physically or mechanically unbalanced cylinders.

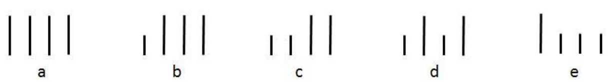

Figure 3: Possible patterns for gain modifications.

A test has been conducted on the basis of 15 stimuli. Each pattern from Figure 3 has been considered with 3 gain values (see details in Table 1) and applied to modify the main combustion process components. This set of sounds has been designed after several listening sessions, in order to optimize the number of stimuli, their overall loudness, etc. These discussions were necessary, as the signal processing tools and methodology we operated can generate a very wide field of sounds and effects.

Table 1: Patterns and gains used for test stimuli.

pattern	gain #1	gain #2	gain #3
a	0,0,0,0	1,1,1,1	2,2,2,2
b	0,1,1,1	0,2,2,2	1,2,2,2
c	0,0,1,1	0,0,2,2	1,1,2,2
d	0,1,0,1	0,2,0,2	1,2,1,2
e	1,0,0,0	2,0,0,0	2,1,1,1

3.3 Test protocol

As engine sounds to be heard come from microphones placed in an engine test bench – and not in a usual passenger compartment, listeners were told that they were listening to the noise coming from the engine compartment as if they had opened the bonnet of their car.

Two types of test were conducted during the same listening session.

In a first time a dissimilarity test was proposed to listeners, during which they were asked to evaluate the similarity between sounds by moving a cursor on a scale, fitted with two extreme labels : ”identical” (left) and ”very different” (right). A perceptual map is constructed *a posteriori*, using test results and a multidimensional scaling (MDS) procedure [8].

In a second time, a monadic test was conducted in order to obtain a quality scale. Listeners were asked to evaluate the quality of the engine setup, by moving a cursor on a scale fitted with two extreme labels : ”badly set up” (left) and ”well set up” (right), according to the noise coming from it.

About 50 subjects took part in the test. Results are presented and discussed in the next section.

4 Test results

4.1 Dissimilarity test

From dissimilarities perceived between stimuli by subjects, MDS method establishes different perceptual maps according to the number of dimensions used. In our case, after stress variable calculation, two dimensions can be used for the perceptual map, shown in Figure 4. These two main perceptual dimensions have been used by subjects to evaluate the similarity between stimuli (– their signification is not known *a priori*). It is noticeable that the three distinguishable groups in the perceptual map correspond to the three gain patterns described in Table 1.

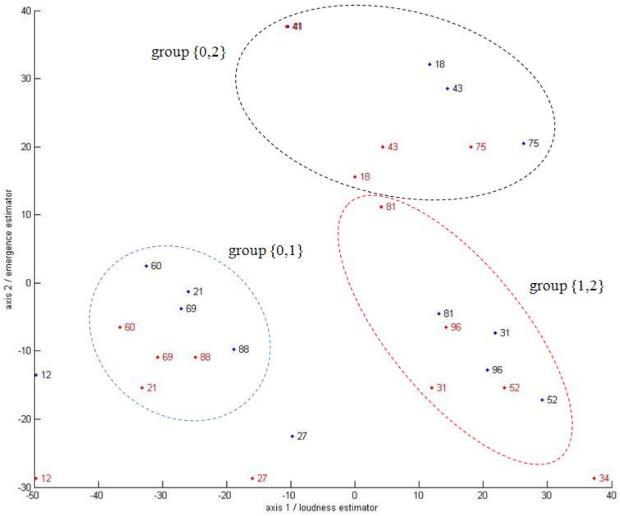

Figure 4: Perceptual map (black points) and loudness/emergence estimators map (red points).

A posteriori stimuli listening tests have lead to the following conclusions: Two auditory streams [2, 5, 9, 10] are heard in the stimuli : a ”continuous” or ”stationary” stream and a ”knocking” stream. Perceptual dimensions can be interpreted by these two streams.

- First dimension corresponds to the loudness of the two streams. Stimuli ranking on this axis can be explained by the overall level of the different impulsive events in a cycle. Stimuli are indeed separated in two parts on that dimension: stimuli with low level gains ({0,1}) on the left, stimuli with higher level gains ({0,2} and {1,2}) on the right of the axis.

- Second dimension represents the emergence of the second stream (”knock”). Two parameters have an influence on the stimuli ranking on this axis. The first one is the gap between the two levels of the gains applied to the different cylinders in a cycle. It explains the separation of the axis in two parts: stimuli with a gap equal to 1 (gains {0,1} and gains {1,2}) at the bottom, stimuli with a gap equal to 2 (gains {0,2}) at the top of the axis. The second parameter, whose influence is lower, is the density of high level auto-ignitions in a cycle. It explains stimuli ranking in the groups with same gain levels (the groups {0,1}, {0,2} and {1,2}). Pattern ”b” has three high level impulses in a cycle, patterns ”c” and ”d” have two and pattern ”e” has one. We can observe indeed that patterns are ranked on this axis, for each group with the same gain levels, in decreasing order of this parameter : patterns are ranked in the order ”b”, ”c”, ”d” and ”e”, pattern ”e” being the most knocking one.

These interpretations are validated by physical estimators, computed on signals used for stimuli. Tested estimators show that a loudness estimator describes correctly the first perceptual axis and that an emergence estimator well describes the second one. The resulting physical map is shown in Figure 4 (red points), where we can observe a very good agreement between physical and perceptual maps.

4.2 Monoadic test

Subjects have been found to be consensual and stimuli to be well spread and distinguished on the quality scale (see Figures 5 and 6).

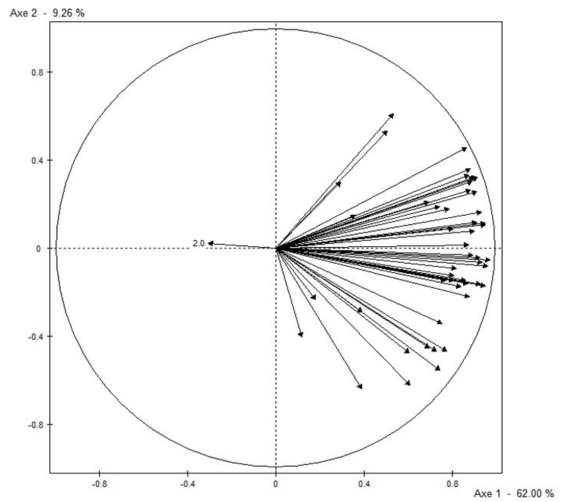

Figure 5: Principal component analysis.

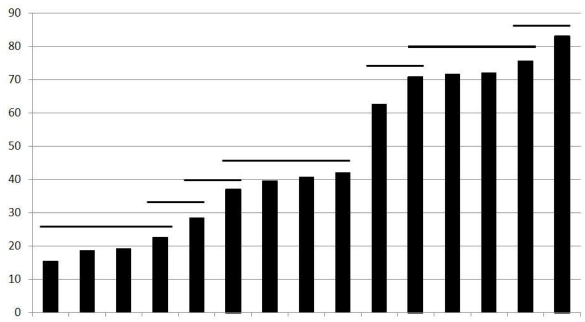

Figure 6: Duncan graph.

Influence on setup quality of the in-cylinder pressure modification parameters used to design stimuli will not be discussed here. However, it must be underlined that setup quality is linked to the two axes described previously.
A linear regression using these two dimensions for approaching the setup quality leads to a $R^2 = 0,92$ correlation coefficient. Thus, setup quality can be written as " setupquality = A loudness + B knockemergence ". Furthermore, a $R^2 = 0,94$ correlation coefficient is obtained when using the two objective physical estimators for these two perceptual axes.

One global important conclusion is that rhythmic patterns produced by different physical "irregularities" are significantly involved in the perception of Diesel combusion noise and that, in some cases, its role can be more important than the overall combustion noise level.

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