Perceptual evaluation of the influence of the estimation of Wiener filters applied to engine noise

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Sound source separation in diesel engines can be implemented using a Wiener filter or spectrofilter that can extract the combustion contribution from the overall noise. This filter characterizes the transfer function between a cylinder pressure and a measurement point. Thus, a spectrofilter is computed for each cylinder, which induces that an engine is represented by several filters. Its computation depends on operating conditions, which makes the full characterization of the engine very time consuming. The goal of this study is to determine filter parameters modifying the perception of these sounds. An experiment has shown that the engine timbre is mainly dominated by the cylinder pressure. This allows the use of an averaged filter that can be applied to all operating points without lowering the accuracy of the source separation. To that purpose, modal parameters are identified for several spectrofilters to estimate them in the most efficient way, while allowing a good reconstruction. Perceptual experiments are conducted to analyze the effects of this estimation on the combustion noise.

1 Introduction

In spite of the efforts of car manufacturers, diesel engines are still noisier than gasoline ones. This is due to the combustion process, which creates very high cylinder pressure values in diesel engines.

Many studies have been conducted in order to understand the propagation of combustion noise through the engine and to evaluate its contribution to the overall noise radiated by the engine ([1-3]). Most of these studies were limited to physical characterization of the transfer paths but some of them considered how sounds are perceived by a listener. As an example, Nykänen et al. [4] determined the accuracy of binaural transfer functions (between the engine compartment and the cabin) which is needed for an accurate auralization of the engine sound.

The overall noise of the diesel engine can be separated in two sources: the combustion and the mechanical noise. Several techniques enable to separate these two parts, for example the Combustion Noise Meter system [5], which consists in filtering the pressure measured in the cylinder by an averaged structural response and an A-weighting curve. This device allows the quantification of the combustion noise but cannot be used for sound synthesis. For this latter purpose, more sophisticated techniques have been proposed. One of them is based on the estimation of a Wiener filter (also called spectrofilter and developed in [6]) between the cylinder pressures and the microphone signal.

The first part of this paper will describe the relation between the combustion noise and the Wiener filter by explaining the extraction procedure, presenting a preliminary listening experiment and developing the method which allows the identification of the modal parameters of this filter. The second part will expose the perceptual analysis of the estimations of the spectrofilter.

2 Combustion noise and spectrofilter

The combustion noise is computed by the convolution of the cylinder pressure and the spectrofilter. To understand the perception of this noise, it is important to know the relation between the combustion noise and the Wiener filter.

2.1 Extraction procedure

The spectrofilter enables to generate the noise due to the cylinder pressure. The computation of this filter requires the identification of the cylinder contribution in the microphone signal. This is realized by temporal windowing. The length of the window decreases when increasing the rotation speed. Thus an error is introduced because the damping ratio is artificially changed [7]. In this study, it is assumed that the engine behaves as a time invariant linear system. Thus physical parameters should not be too sensitive to operating conditions.

As the specrofilter computation is very time-consuming, and has to be made for all operating conditions (load and rpm), the determination of a common filter appears useful. The frequency response functions (FRFs) of the spectrofilters in various operating conditions reveal the possibility to create a common one, because of their similarity illustrated in figure 1.

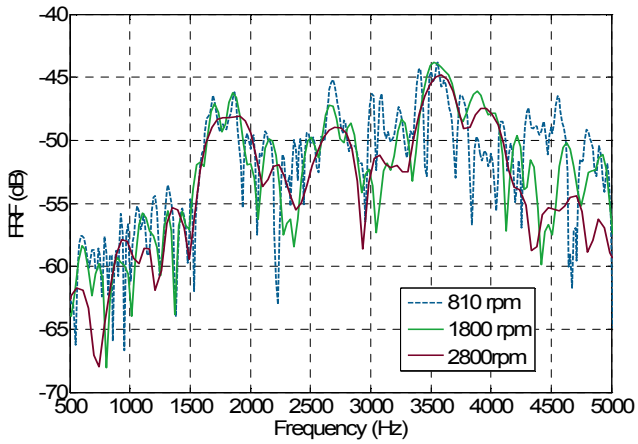

Figure 1: FRF magnitude of the spectrofilters computed in different operating conditions

The combustion noise depends on the cylinder pressure and the Wiener filter, but it is necessary to know if one of them dominates some noise characteristics.

2.2 Perceptive preliminary study

The aim of this study was to evaluate the relative contributions of the cylinder pressure and the filter characteristics in the timbre of combustion and mechanical noises. Two experiments were conducted, one for each of these two noises. Three operating conditions were used to create nine sounds: the cylinder pressures (P1, P2, P3) and the spectrofilters (S1, S2, S3) were mixed as in table 1.

Table 1 : Listening test noise computation

	S1	S2	S3
P1	son 1	son 2	son 3
P2	son 4	son 5	son 6
P3	son 7	son 8	son 9

The sounds were presented to 28 subjects (22 males and 6 females between 20 and 30 years old) in a free sorting experiment. Listeners had to group sounds together, on a basis of timbre similarity. Sounds were presented by two speakers in a sound-proofed booth. They could be heard as many times as necessary.

The results of each listener were recorded in a co-occurrence matrix, only composed by 1 and 0. Individual matrices were averaged to obtain the distance matrix.

The distance between the sounds is represented in a graphic called dendrogram in figure 2.

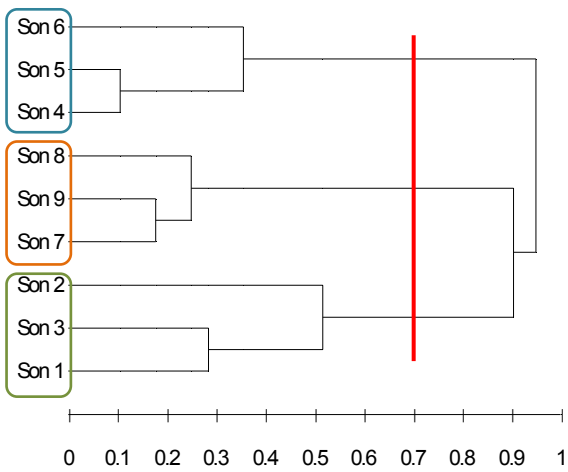

Figure 2 : Dendrogram of the listening test of combustion noises

Figure 2 shows that the sounds can be separated in three classes. Table 1 enables to conclude that each group corresponds to a cylinder pressure. Thus, the combustion noise timbre is dominated by the cylinder pressure and not by the Wiener filter. The same conclusion was obtained for mechanical noise. Thus the use of a common spectrofilter seems possible.

The difficult point is how to synthesize this common filter. In fact, the modal density is important as shown in [8].

2.3 Identification of modal parameters

Even if the FRF of the filters in different operating conditions are similar, the identification of common modal components is not easy. In fact, the common components have to be characteristic of the structure, so the information has to be sorted.

Several methods estimate a signal on a basis of complex exponential functions. The size of this basis can be changed. Therefore the impulse response function can be estimated with a limited number of exponentials, so the information will be reduced.

The ESPRIT method [9] was the most adapted one in this study. The number of identified modal parameters is important. If it is lower than the real number of modes, the identification of the modal parameters will not be accurate. The introduced error is proportional to the distance at the real number of modes. On the contrary, when it is higher, the modal components are exactly identified, but are flooded into false components. In this case, the method creates other modes to satisfy the number required. In this study, the spectrofilter modes number is unknown. Thus, the ESTER criterion is used to determine this number [9].

As the Wiener filter is computed for each operating point, a selection is established. The study was carried out at nine operating conditions presented in table 2. ESTER is applied on all of these selected filters. The calculated value K of the modal components of each filter is deduced. It is important to note that the ESTER criterion is a little subjective, and in this study it is difficult to define an accurate K value.

Table 2 : Operating conditions selected for the study

rpm	810	1050	1300	1550	1800
load (Nm)	60	105	152	151	140
K	160	120	80	85	63

rpm	2050	2250	2550	2800
load (Nm)	152	148	81	144
K	55	48	39	39

The length of the vector K is 8 because the ESTER method gave the same values at 2550 and 2800 rpm. In general, when increasing the rpm, the number of modes decreases. This is also due to the windowing applied during the computation which smoothes the filter spectrum.

The paradox between the theory and the measurements engages some reflexions. In theory the same number of modes should be detected in all the filters, but in practise it differs because of the error in the computation. The principal issue concerns the number of useful modes to create the common filter. In fact, it has to be well estimated in signal processing, but also this estimation has to separate enough accurately the combustion and mechanical noise in perception.

Thus a perceptive study was led to define relations between combustion noise, studied in part 2.2, and the Wiener filter estimations as presented in this part 2.3.

3 Perceptive analysis of the spectrofilter estimations

The purpose of this listening experiment was to determine some limits about the number of modes necessary to estimate the filters allowing an accurate enough noise separation.

3.1 Experimental setup

Using the whole set of operating conditions described in part 2.3 would have led to very time consuming experiment. Therefore four rotation speeds were selected (810, 1050, 1800 and 2250 rpm) in order to limit the duration of the experiment below 30 minutes.

Thus, the experiment was divided in four listening tests, each of them dealing with one of the selected operating conditions. Each test was a free-sorting one of ten sounds : the original noise, which appeared twice and eight other ones computed with the K spectrofilter estimations presented in part 2.3. The conditions (under/over/ideal) to assess the Wiener filter, according to the K values, and the corresponding sounds are given in table 3.

Table 3 : Estimation (under/over/ideal) conditions according to the number K of identified modal parameters

Sound	*K*	*810 rpm*	*1050 rpm*	*1800 rpm*	*2250 rpm*
(2)	*39*	under	under	under	under
(3)	*48*	under	under	under	***ideal***
(4)	*55*	under	under	under	over
(5)	*63*	under	under	***ideal***	over
(6)	*80*	under	under	over	over
(7)	*85*	under	under	over	over
(8)	*120*	under	***ideal***	over	over
(9)	*160*	***ideal***	over	over	over

The experimental setup was identical for each test. Sounds were presented through headphones (Sennheiser HD600) in the sound-proofed booth. Sound level was adjusted at 67 dB(A), using a dummy head (Cortex).

24 listeners (6 female and 18 male) participated to the experiment, so that the order of the four tests could be balanced between listeners.

3.2 Results and discussion

The results were observed by auditors, in order to determine if some groups have a similar agglomeration strategy.

3.2.1 Subjects variability

The purpose of this study was to define the filter estimations which enable an accurate combustion noise extraction. The analysis is more quantitative than qualitative. In fact, the aim was to determine the sounds that were not associated with another or not included in any class.

The Rand Index is an estimator of the similarity between sortings made by two listeners. The Asymmetric Rand Index (ARI) can be more efficient to compare two auditor partitions when class number is different. In this case, the distances represent the inclusion of classes of a listener in a class of another listener. Thus, the results of this experiment were analyzed with the ARI. Dendrograms of the ARI showed that no auditor group can be identified, except in the test 4, illustrated in figure 3.

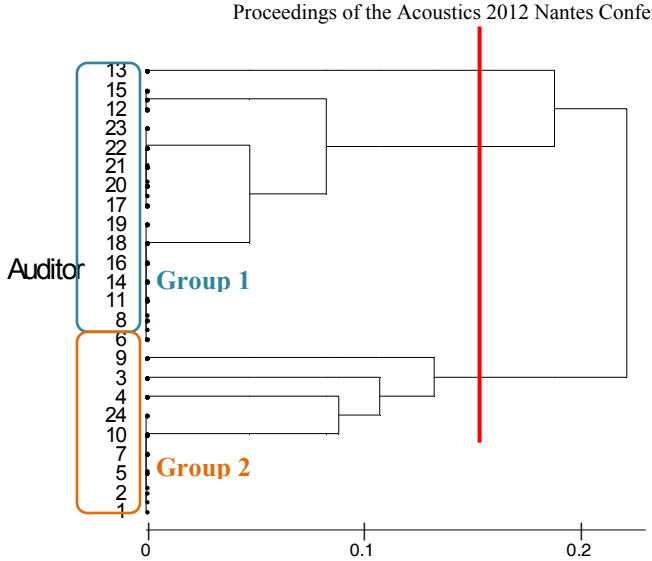

Figure 3 : Dendrogram of the ARI computed on the auditors of the test 4

Two groups clearly appeared. They were composed by 18 persons (group 1) and by 9 persons (group 2). Therefore, while the averaged distance matrix was computed over the whole panel for the first three operating conditions, this was done separately for the two subjects groups in the last condition.

3.2.2 Sounds groups

The dendrograms at low rpm (test 1 and 2) were similar because one class was clearly separated. It was composed by the sounds 1, 8, 9 and 10. The sounds 1 and 10 were the two presentations of the original noise, so it could be expected that they were agglomerated together. The sounds 8 and 9 correspond to the highest values of K. In theory, when a signal is under-estimated, the error of modal parameter identification and the error of signal reconstruction are high, as explained in part 2.3. Thus, the best condition is for the ideal value of K and in over-estimation.

The relation between the assessment conditions and the accuracy of signal reconstruction was verified in the results of the tests 1, 2 and 3. The dendrogram of the 1800 rpm can be decomposed in 4 sound classes : (2), (3), (4), (1,10,5,6,8,7,9). The group corresponds at the ideal and over estimations, according to the table 3. This result can also be represented by the figure 4, which illustrates the first line of the distance matrix. Consequently, when the distance is 0 the sounds listen similar and it is 1 when they are judged totally different.

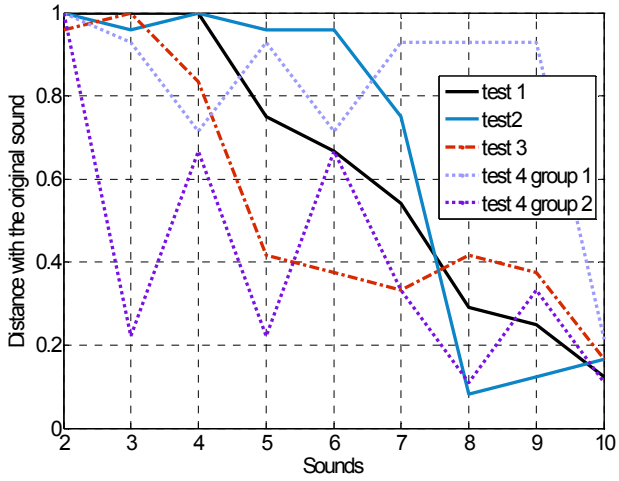

Figure 4 : Distance of each sounds with the sound 1 (original combustion noise)

A relation can be easily established between the number of identified modes (table 3) and the perceptive distance of each estimated noises with the original one (figure 4), except for 2250 rpm.

For the highest rpm condition, the sound dendrograms had to be calculated for each auditor class. For the group 1, four sound classes can be separated : (1,10) ; (6,4) ; (2) and (3,7,9,5,8). The group 2 of the test 4 has defined three classes : (1,8,5,10,3,7,9) ; (6,4) and (2). The unique similitude is that the sound 2 is not classified with another. This result is in accordance with the table 3. Nonetheless, the group composed by the sounds 4 and 6 is always lately connected to the others, which induces that they sounds different. The problem is that numerically the Wiener filter spectra are not so different, as illustrated in figure 5.

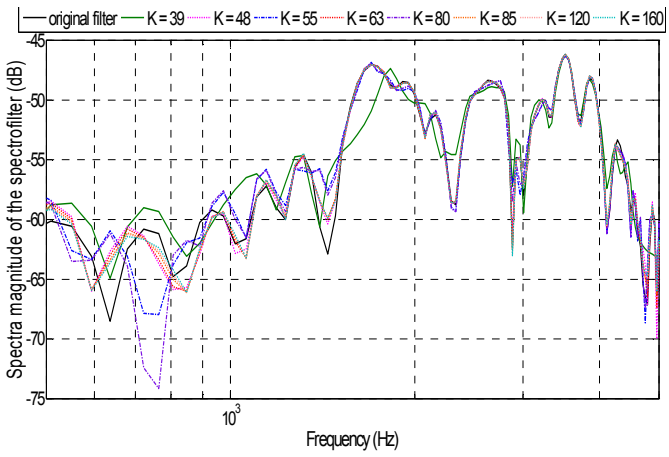

Figure 5 : Spectra magnitude (dB) of the spectrofilters at 2250 rpm

The few differences observed in [400;1500] Hz are less than 5 dB, and in band of low energy. Only the filter assessed with 55 and 80 modes (dash-dot plot) have a great deviation of nearly 15 dB at 750 Hz. It is possible to identify the four groups of filters, with K values, corresponding to the classes : (39); (55, 80); the original, and all the rest. As the filter is applied to the cylinder pressure, it can be supposed that there would not have an important effect on the combustion noise; but it is sufficient to have an effect on the perception.

In order to understand this phenomenon, spectra of four sounds (one by class) were plotted in figure 6. A deviation of 5 dB maximum is observed between 400 and 1500 Hz. This is located in the high energy frequency band, so it can explain the listener sorting. For the sound 8, the tendency is very similar to the original sound but is not accurate enough estimated in perception.

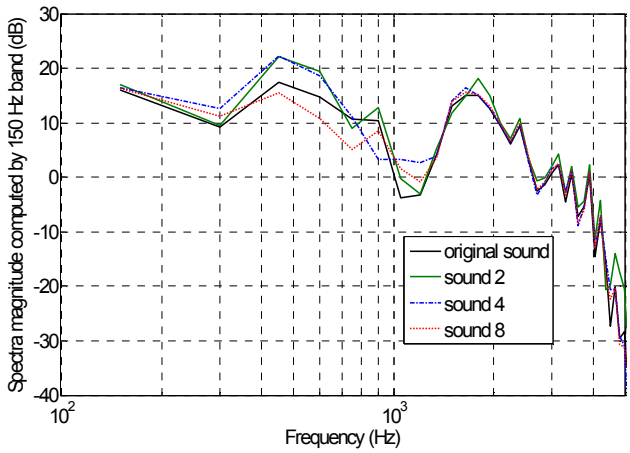

Figure 6 : Spectral magnitude (dB) of the sounds at 2250 rpm averaged on 150 Hz band

The specific loudness of the original noise and the sounds (3,5,7,8,9) are plotted in figure 7 to define more precisely the frequencies of the dissimilarity.

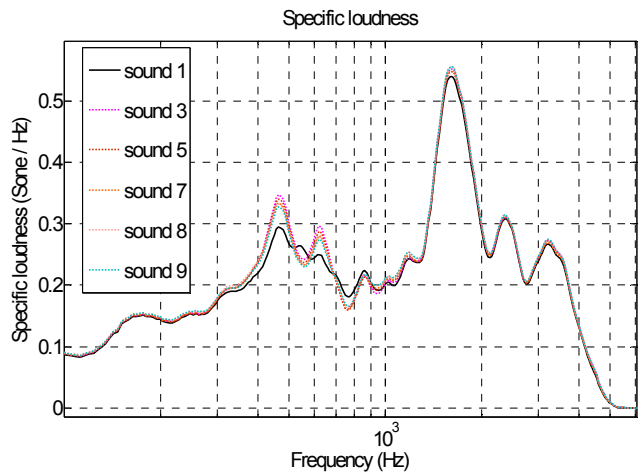

Figure 7 : Specific loudness with frequency of the sounds 3, 5, 7, 8, 9 and the original

The specific loudness, in figure 7, shows that the dissimilarity between the original and these estimated sounds is in the [500 Hz; 800 Hz] band. Consequently it is necessary to obtain an accurate assessment of the spectrofilter in this frequency band. In fact, the cylinder pressure energy is high in the [400 Hz;1000 Hz] band so the small deviations in the Wiener filter in this frequency band will be amplified.

This experiment has shown the effect of the estimation conditions of the spectrofilter on the perception of the combustion noise. For the low running engine, an assessment computed on 120 modes enables an accurate enough combustion separation. In the test 4, at 2250 rpm, estimation of the Wiener filters was not good enough in the [500 Hz;1500 Hz] band, which induces a low perceived

similarity. This reveals that this frequency band is important for the combustion noise listening.

4 Conclusion

The purpose of this paper was to identify the effect in perception of the number of modes used to estimate a signal. The studied signal was a Wiener filter which is applied to the cylinder pressure to extract the combustion noise. A first part exposed preliminary results about some combustion noise characteristics. It also presented the signal processing study which had to be completed by this perceptive analysis. Several filter estimations were computed. Some of them look similar to the original filter. Thus it was logical to think that these estimations would extract similar combustion noises. Nonetheless, the listening experiment had shown that this is not always true. For low engine speed conditions, the listening test results were in accordance with the signal processing theory and have shown that 120 modes are sufficient to synthesize the filters. The difficulty relies in higher rpm. Even if the filter spectra looked similar, the sounds were agglomerated in different groups. Therefore the excitation patterns of the sounds were plotted. It showed that the problem is located between 400 and 1500 Hz. This represents a frequency band of low energy of the filter, which induces that the ESPRIT estimation of the filter is not accurate, because few modes are identified in this band. The cylinder pressure energy is important in this band so when the filter is applied, the little differences are amplified.

Finally it is difficult to define the number of modes characteristic of all operating conditions. Nonetheless the problem determined by the experiment is linked to the ESPRIT capacities. So it could be possible to try a synthesis of a common filter based on 120 modal components. Future works will define these components for a low speed operating condition and validate the common filter in a perceptive study led on combustion noises computed with this filter in different operating conditions.

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