Noise source separation in diesel engines: application to acoustic listening tests

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Abstract

This article discusses the extraction of combustion noise from diesel engines using a Wiener filter. Using the ESPRIT method, the filter is set to a limited number of modes, in order to reduce the amount of information it contains. It is estimated for various engine settings (load and engine speed). For this reason, real filters and their estimations are used to synthesise the noises. A perceptive experiment is conducted on these sounds in order to ensure that certain parameter filters enable the extraction of sounds similar to the combustion noises obtained by the measured filters. The aim of this work is therefore to evaluate the influence of the filter estimation conditions on the perception of the combustion noises that they help to synthesise.

1 Introduction

The reduction of diesel engine noise inside the passenger compartment can be achieved by modifying the transfer between the passenger compartment and the engine compartment, or by directly intervening at the source. Work carried out on the engine is generally related to identifying and ranking sound sources, and, more specifically, combustion noise. Combustion noise seems to be the noise that customers find most annoying. Much research has therefore been carried out on isolating this noise, such as the Combustion Noise Meter [1]. As the purpose of this study is to carry out a perceptive analysis of this noise, special attention is paid to the choice of extraction method. The Wiener filter appears to be the most suitable choice [2]. This filter is very accurate, as it characterise each cylinder, and it must be updated each time the engine settings are modified. The filter calculation requires much preparatory work, such as synchronisation of the cycles and temporal windowing, which isolate the noises of the cylinder in question. Therefore, the intention is to create a common Wiener filter that can be applied to all operating points, and will result in the identification of the characteristic engine settings. Several filters, obtained at different operating points are therefore set to a reduced number of modes, in order to obtain the minimum amount of information necessary to reconstruct the filter. A perceptive analysis of the noises synthesised by these filter estimations confirms the extraction of the modal parameters. However, no comparison can be made to similar studies. Perceptive research, until now, mainly discusses the whole engine noise [3,4]. A recent study [5] dealt with isolating combustion noise using a Weiner filter that had different properties to those defined in this article. This study looked at the amplitude variability of the combustions between each cylinder, whilst the present study is interested in the perceptive analysis of synthesised combustion noises using parameter Wiener filters.

The terms used in this article shall be given in the first part of the document, as will the spectrofilter calculation. Then the filter parameters measured at several operating points will be extracted. The number of engine modes studied remains unknown [6], but an estimation can be made. To do so, the ESTER [7] technique will be used, as it indicates the number of modes to be extracted, which minimises mistakes in reconstructing the signal. Then, the ESPRIT method is optimised before being applied to these filters. In order to confirm the parametrical estimations of the Wiener filter, a perceptive experiment will be carried out on the synthesised sounds. The aim is to define the sounds that are similar to combustion sounds, calculated using the measured spectrofilters.

2 Separation of the Engine Sound Sources

2.1 Basic Notions

The sound of an engine can be separated into several sound sources. This study will separate the noise into just two sources: combustion noise and mechanical noise. Combustion noise originates from acoustic phenomena caused by the rapid rise in pressure in the cylinders, which is characteristic of combustion. Mechanical noise includes the sound components of all the other operating parts of the engine.

In practice, several techniques have been developed [1] to separate combustion noise. The purpose of the work discussed in this article is to perform a perceptive study on this noise, for various engine settings, such as injection. As a result, this separation must be accurate enough to be able to identify the perceptive criteria. This led to the use of a Wiener filter, also referred to as a spectrofilter [8]. This filter is applied to the pressure cylinder in order to extract the combustion sounds, which can be represented as a diagram using the system in Figure 1.

Figure 1: Combustion noise extraction system

In [9], a simple perceptive experiment was carried out on three operating points by switching the filters and cylinder pressures in order to obtain nine combustion noises. A free sorting test was presented to the subjects, which asked them to sort the sounds by similarity. Combustion noises were grouped by cylinder pressure, and not by filter. The same procedure was used with the respective mechanical noises. It follows that the tone of the engine sound sources is dominated by cylinder pressure.

2.2 Spectrofilter

The Wiener filter used in this study must be calculated at each change in engine settings (such as a change in load or engine speed). It is based on the cyclostationarity of the engine signals and is therefore determined for one cycle (two rotations of the crankshaft). This means dividing the signals per cycle, depending on the angular position of the crankshaft. Subsequently, the analysis may be angular [10] or temporal [11]. In this case, time synchronisation is achieved using the top dead centre, for example. This filter can only qualify one cylinder, so it is necessary to isolate the sounds of the cylinder from the engine sounds, recorded with a microphone. These sounds are extracted using temporal filtering, which is time-synchronised with the cylinder pressure [2], as shown in Figure 2.

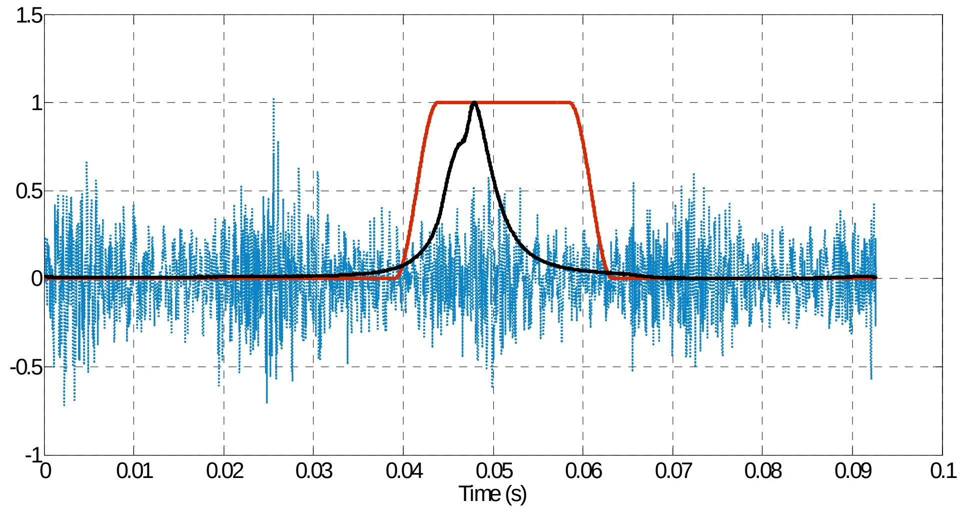

Figure 2: Time window (red) synchronised to the cylinder pressure (black) applied to the engine noise (blue)

Giving the average per cycle provides the determining part of the signals. In order to reduce bias errors, the spectrofilter is calculated from random parts. These parts can not be identified below 500 Hz, as they are drowned out by the measurement noise. Above 5000 Hz combustion chamber cavity modes appear, and in this case, the pressure can only be considered as even. Therefore, the Wiener filter is only defined for [500-5000] Hz. It is obtained using the H1 estimator between the cylinder pressure and the filtered engine noise.

For each modification of the engine settings, this whole procedure is to be applied in order to obtain the spectrofilter isolating the combustion noise. As this step is long, the application of a common filter could be interesting. However, creating such a filter requires the selection of characteristic information on the structure, such as modal parameters. The aim is therefore to define the minimum number of modes necessary to estimate the measured filters, enabling a perceptively accurate separation of the combustion noises.

3 Extraction of Modal Parameters and estimations of Measured Spectrofilters

The characteristics of the spectrofilter mean that it is a suitable choice of modal analysis method [12,13]. A study [14] on filters defined the ESPRIT method to be the most appropriate method.

3.1 Optimisation of the ESPRIT Method

ESPRIT [13] is based on the hypothesis that the measured signal contains a white noise for dividing this signal based on complex exponential curves. Therefore, identifying the modes was carried out in high-energy frequency bands [14]. However, between 500 and 1500 Hz the spectrum has up to 15 dB less than the rest of the frequency domain. This is not in accordance with the white noise hypothesis. Two approaches can compensate for this point: a study per frequency band [15], or whitening the spectrum [7]. As the number of dominant modes in each frequency band is unknown, whitening seems to be the most suitable method. In order to readjust the spectrum, an energy correction of 600 Hz is made for each band: the signal is divided in each frequency band, the energies of each piece of signal are calculated, then applied respectively, in order to "standardise" the energy in each section of signal. The aim is to conduct crude whitening of the spectrofilter in order to extract the modal components for the whole area of filter definition, as illustrated in Figure 3.

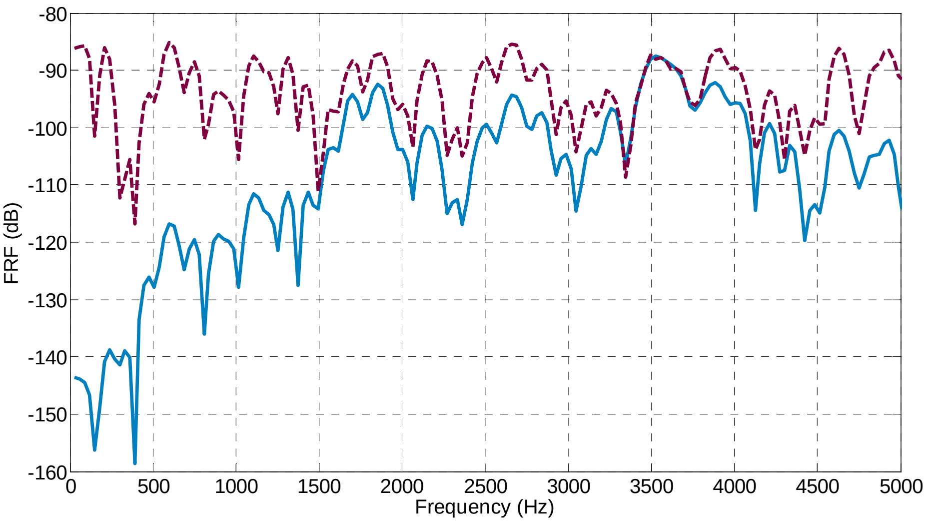

Figure 3: Spectrofilter (blue) and whitened spectrofilter (red dotted line)

This method requires an estimation of the number of modal components to be extracted, referred to here as K. However, for the structure being considered, which was previously modelled for other applications [6], the number of modes that exist is high, but remains unknown. The ESTER technique can solve this problem [7]. It indicates the estimation error for the signal obtained for a certain number of K values. Therefore, this technique defines a K number of modes to be extracted, in order to reduce errors in synthesising the signal. This technique is therefore applied to filters measured on a running engine, in order to obtain a K value for extracting their modal components with ESPRIT.

3.2 Application on Measured Spectrofilters

Wiener filters are determined on a 1.9 L diesel engine at different operating points. The acquired signals are processed as explained in section 2.2. The spectrofilters obtained are shown in Figure 4. It is interesting to note that the filter spectrum is smoothed when the engine speed increases which also leads to an apparent increase in damping, observed in [14]; this is linked to the reduced duration of the analysis windows, set to quarter cycles.

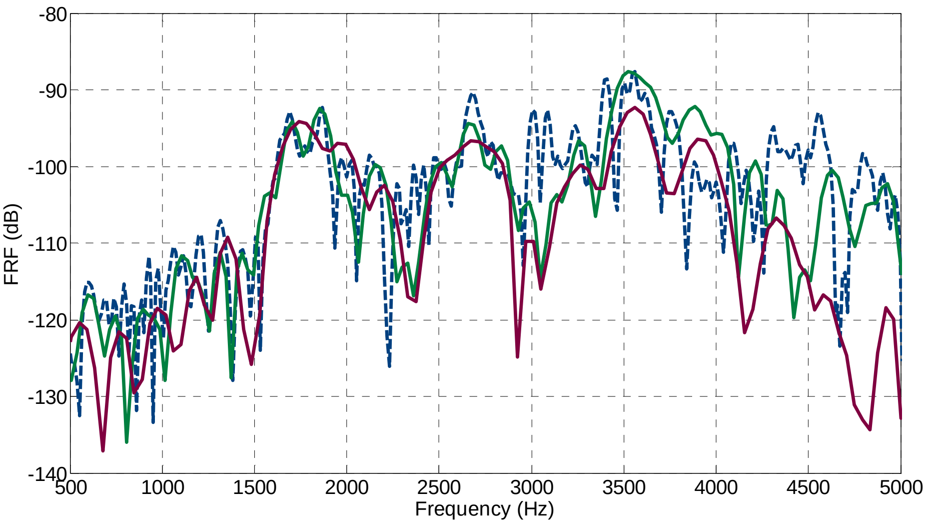

Figure 4: Wiener filters measured at 810 rpm (blue dashes), 1800 rpm (green), and 2800 rpm (red)

The values from ESTER can be associated with this smoothing of the spectrum. The number of modes to be extracted, K, obtained for each operating point decreases when the engine speed increases, as shown in Table 1.

rpm	810	1,050	1,300	1,550	1,800	2,050	2,250	2,550	2,800
load (Nm)	60	105	152	151	140	152	148	81	144
K	160	120	80	85	63	55	48	39	39

Table 1: Engine settings and their respective K values

The ESPRIT method is applied to each filter with the eight K values. Therefore 72 parameter estimations for Wiener filters are obtained in all the estimation conditions: for the K value indicated by ESTER (optimum condition), for lower values (underestimation) and higher values (overestimation), illustrated in Figure 5.

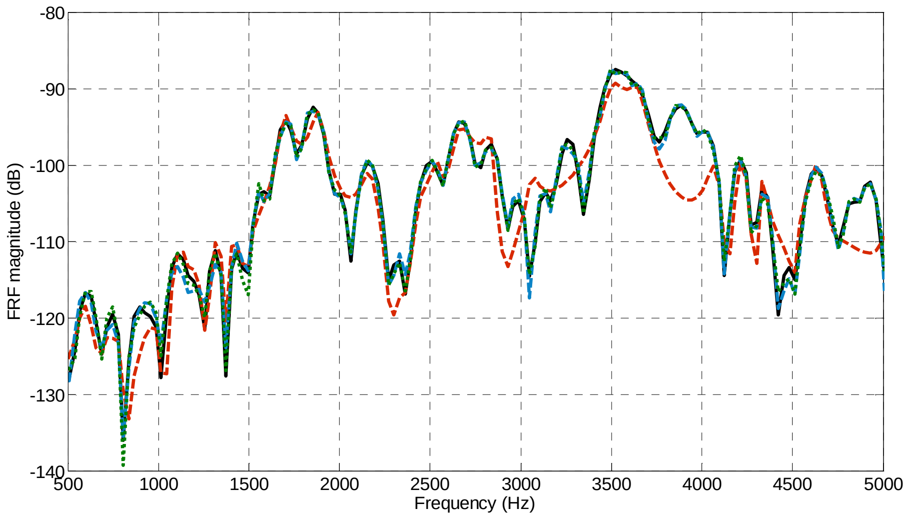

Figure 5: Spectrofilter at 1800 rpm (black) and its estimations - underestimation (red dashes), optimum condition (blue dashes) and overestimation (green dotted line)

It would seem that in underestimation, reconstruction is wrong, whilst for the optimal K value and in overestimation, estimation is accurate. Nevertheless, as the final application is the perceptive study of the noises synthesised by these estimations, an experiment is carried out in order to define the minimum number of modes necessary to estimate the filter and enable accurate extraction of the combustion noise.

4 Perceptive Study of Synthesised Noises

4.1 Protocol

The experiment cannot be based on all the engine settings used in section 3.2, as this would take too much time. In order to limit the test duration to 30 minutes, only four operating points (810, 1050, 1800 and 2250 rpm) are taken into account, thus providing four categorisation tests (free sorting). The procedure is identical for each listening session, 10 sounds are used: the measured combustion noise which is played two times (used as a reference), and the eight noises calculated using the filter estimations. Their sound levels are adjusted 67 dB(A) using a dummy head (Cortex). In order to balance the presentation order, 24 listeners participate to the experiment (6 women and 18 men). The subject is placed in a soundproofed room and the stimuli are listened to through headphones (Sennheirer HD600).

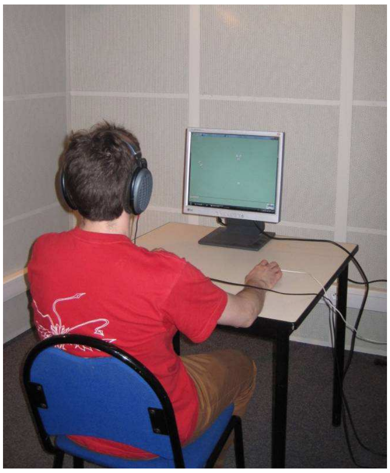
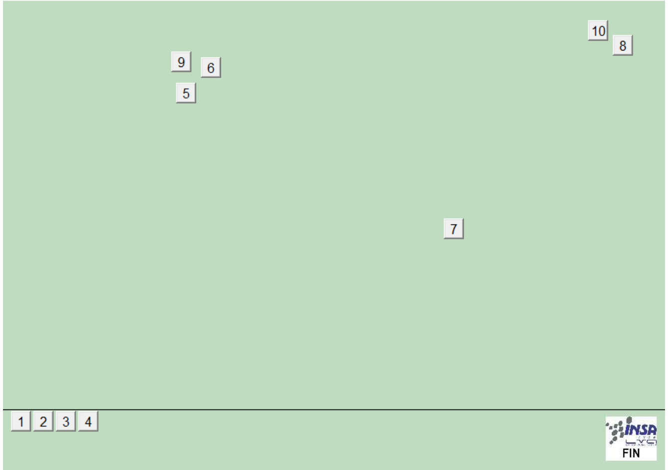

Figure 6: Position of the subject (left) and the screen of the listening session (right)

The subject clicks on a numbered box to hear a stimulus. Each number corresponds to a different sound. The sounds are arranged randomly, and change for each session. When the listener identifies two similar sounds, he/she groups these sounds together on the screen. On the other hand, if the subject deems the sounds to be different, he/she clearly separates them.

4.2 Results and discussions

4.2.1 By Subject

Firstly the free sorting test results are analysed for each listener. The variability in the number of sound classes formed by the listener is significant, so the results are interpreted using the asymmetrical Rand index. This index is calculated per pair of subjects, which enables the establishment of a within subjects distance matrix that can be represented by proximity trees. Those obtained for 810, 1050, and 1800 rpm do not show any dominant category. However, at 2250 rpm three classes appear: a single listener, and two groups. Consequently, the sounds are interpreted by listener group.

4.2.2 By Sound

After calculating the distance matrix, the similarity of stimuli with the original combustion noise is analysed by looking at the first line of the matrix. It indicates the distance from sound 1 of all the other noises. Sounds 1 and 10 are the reference stimuli. Therefore, it is expected that their distance should be nil, as they are identical. Figure 7 shows that this distance is on average 0.15. This value is therefore taken to be the reference value in order to evaluate the similarity between the sounds.

At 810 and 1050 rpm, the optimal K values are 160 and 120 respectively, which corresponds to sounds 9 and 8. Figure 7 allows the numerical observations: for optimum K and the overestimations, the parameter filter estimations are sufficiently accurate, enabling a combustion noise similar to the noise obtained with the measured filter to be synthesised.

At 1800 rpm, the optimal K value corresponds to sound 5. It is interesting to note that from this value on, the distance from the reference stimulus clearly decreases and stabilises at around 0.4. Therefore, the sounds obtained with the overestimations are identical to sound 5, and similar to the reference sound. However, this similarity is less significant than for the low engine speeds as the average distance from the reference sound is higher. Therefore, the estimations from the filter at 1800 rpm are less accurate than for the low engine speeds.

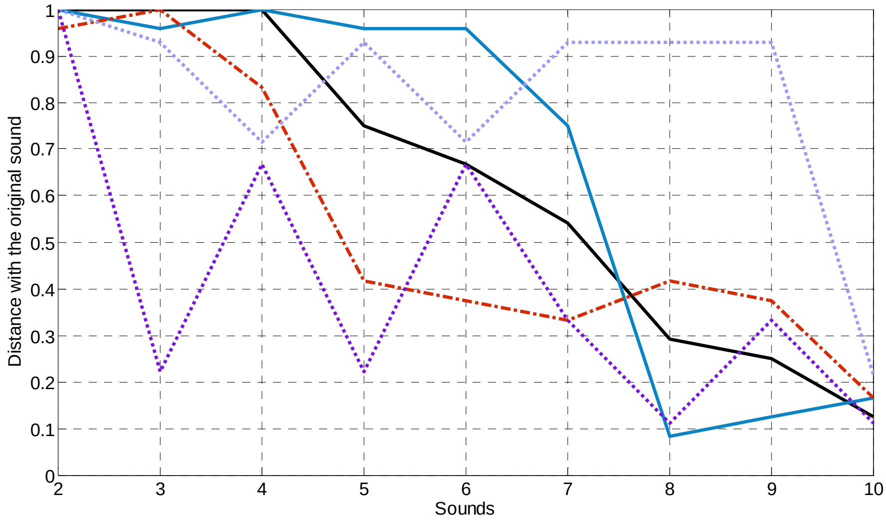

Figure 7: Distance between sound 1 and the other sounds for 810 (blue), 1050 (black), 1800 (red) and 2250 rpm for groups 1 and 2 (dotted light and dark purple lines)

At 2250 rpm, two groups of listeners were identified. For subjects belonging to group 1, all sounds are quite different from the combustion noises measured (sounds 1 and 10). This is not true for listeners in group 2. It is interesting to note that the two groups agreed on sounds 4 and 6: they both have the same distance. In order to understand the contradictory results, the loudness of the stimuli is analysed. As the sounds are very similar, the subjects may have judged the sounds on loudness.

4.2.3 By loudness

Loudness is one of the first perceptive indicators used to distinguish sounds. It indicates how humans perceive the intensity of a sound. Determining loudness therefore requires the use of a model whose input is the recorded signal. In this article, loudness is calculated using the Moore model [16].

To do this, the specific loudness of the stimuli is plotted out for the listening sessions. Figure 8 illustrates it at 1800 rpm.

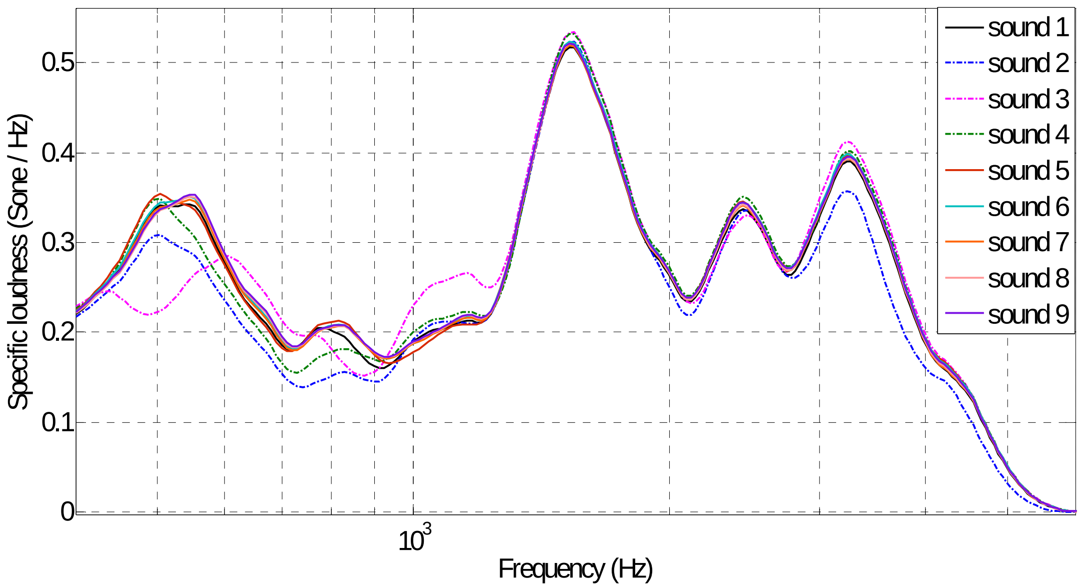

Figure 8: Specific loudness (left) of all the sounds and dendrogram obtained by the sound dissimilarity matrix (right) at 1800 rpm

Specific loudness curves of sounds 2, 3, 4 (dotted lines in Figure 8) - underestimations - are clearly different from the one of the recorded sound (sound 1). These three sounds are also evaluated as dissimilar from sound 1 by subjects, as shown in Figure 9. The same conclusions can be made for the low engine speeds : 810 and 1050 rpm.

The study therefore went further by establishing distance matrixes between specific loudnesses. If these differences, which come from different models, show results that are in accordance with the sound dendograms, this could confirm the hypothesis that the listeners evaluated the stimuli according to its loudness, amongst other factors. One of these is based on a Euclidian distance between the loudness of sound *i* and of sound *j*:

$$de_{ij} = \sqrt{\sum_k \left(s_i[k] - s_j[k]\right)^2} \quad (1)$$

The other distance is based on the maximum relationship between the two loudnesses, which enables the establishment of an average distance from the unit:

$$dr_{ij} = \frac{1}{N} \sum_{k=1}^{N} max\left(\frac{s_i[k]}{s_j[k]} ; \frac{s_j[k]}{s_i[k]}\right) \quad (2)$$

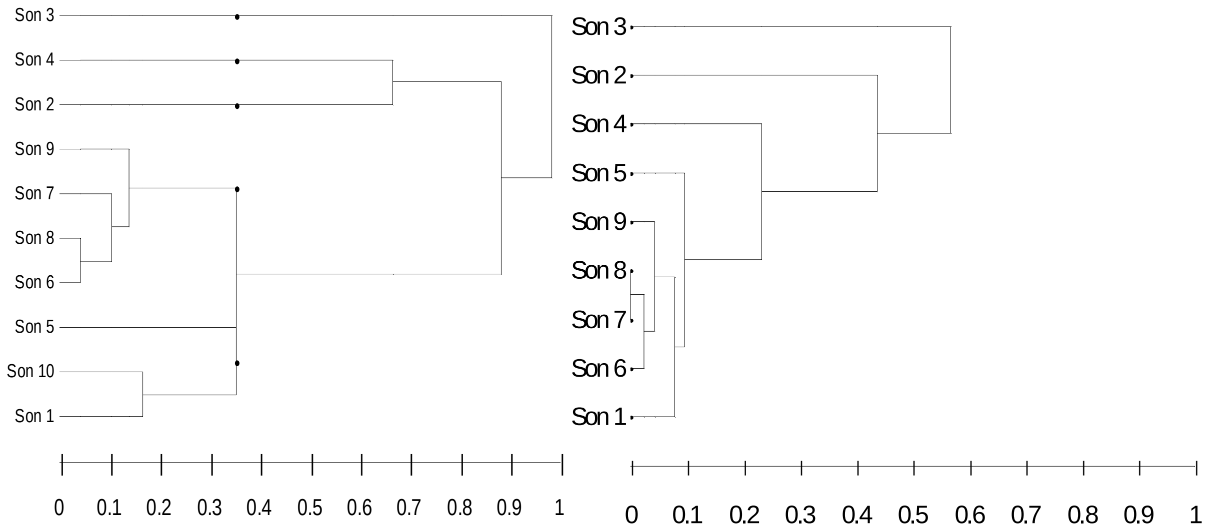

Figure 9: Dendrograms by sounds (left) and by specific loudness (right) in Euclidian distance (eq. 1) at 1800 rpm

Figure 9 shows, on one hand, the exclusion of sounds 2, 3, 4 for the subjects - to the left - and for loudness - to the right. On the other hand, the other sounds are agglomerated in both proximity trees. This indicates that the subjects should have evaluated the similarities of the stimuli principally on their specific loudness. These results are also observed for 810 and 1050 rpm.

For 2250 rpm, two proximity trees are to be analysed. One group identifies all sounds similar to sound 1 - the reference stimuli - except sounds 2 (underestimation), 4 and 6. On the contrary, the other group considers that no estimation is similar to the measured combustion noise.

The specific loudness at this speed, illustrated in Figure 10, shows that sounds 2, 4 and 6 have a specific loudness that is completely different to that of sound 1. As for the others, the only small difference is between [400 - 1500] Hz. This difference was estimated by one group to be small enough to group the sounds with the reference sound. However, the other group of listeners detected this difference and took it into account when classifying it.

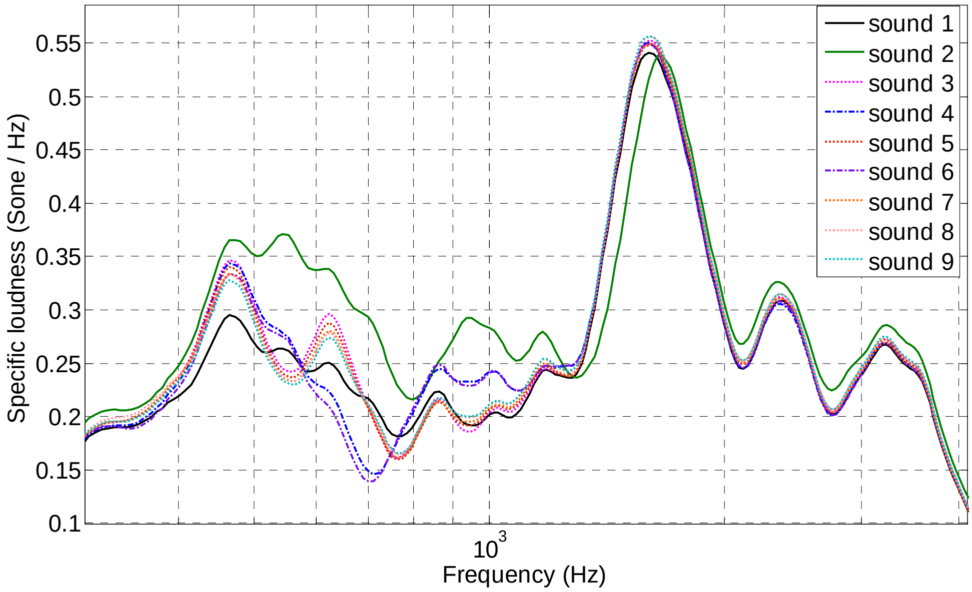

Figure 10: Specific loudness of stimuli at 2250 rpm.

Figure 11 allows the isolation of the sounds 2, the group (4;6) as well as the measured combustion noise (sound 1). The specific loudness of the noises synthesised by the overestimations of the filter are not satisfactory, the cluster difference for these stimuli does not seem to be linked to loudness. As the sounds were very close, it can be explained by the fact that one group of subjects had an agglomerate level more developed than the other group.

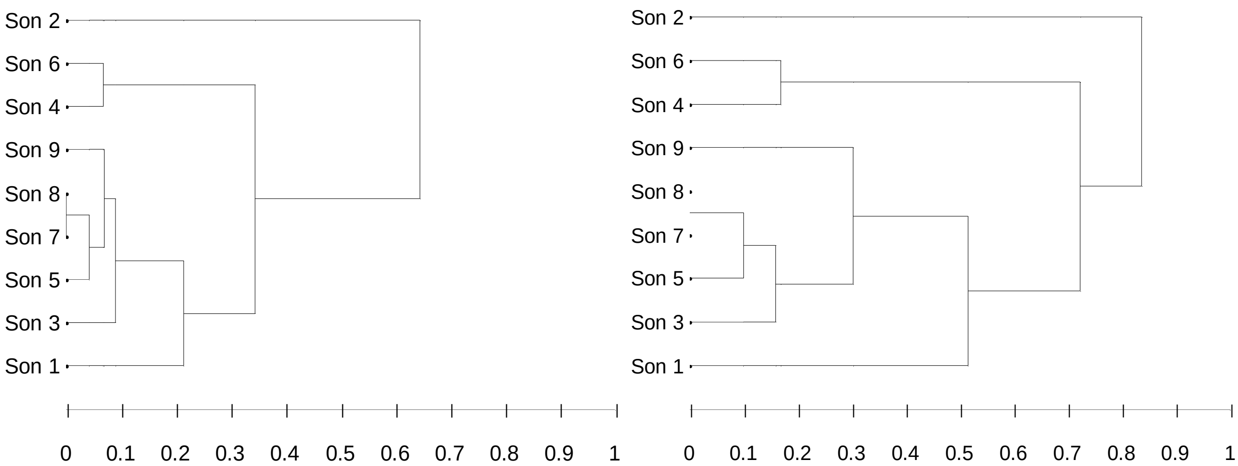

Figure 11: Euclidian distance dendrogram (eq.1) for loudness (left) and distance from the unit (eq.2) and the loudness relationship (right)

Numerically, the filter reconstructions correspond to the measured Wiener filter, except for a few small differences between [400-1500] Hz, which is a low-energy area of the spectrofilter, as shown in section 3.1. However, this frequency band corresponds to the most high-energy area of the cylinder pressure. So the small difference in this frequency band is significant in the synthesised noise spectrum. This phenomenon is shown in Figure 10. The Wiener filter estimation must therefore be particularly accurate below 1.5 kHz when synthesising a combustion noise similar to the one obtained with the measured filer.

5 Conclusion

This article discusses the extraction of combustion noise using a Wiener filter. This filter is estimated on a limited number of modes using the ESPRIT method. This method first requires an estimation of the number of modes to be extracted, which can be evaluated using the ESTER technique. The aim is therefore to define the influence of the spectrofilter estimation conditions on the perception of the noises they synthesise. A perceptive experiment is therefore carried out on four operating points. The stimuli are noises calculated from assessments of the Weiner filter for the operating point being examined. These stimuli are obtained for various estimation conditions that are defined by a number of components (optimum case defined by ESTER, under- and overestimation). In numerical terms, the underestimation does not estimate the filter accurately enough. The procedure is identical for the four free sorting listening sessions: the subject is placed in a soundproofed room, and listens to the sounds using headphones in order to organise them by similarity on the screen provided. If the stimuli are deemed to be similar, they are grouped together on the screen, and if they are deemed to be different, they are spaced out. The results are firstly analysed by listener group using the asymmetrical Rand index. It turns out that no category is identified, except for at 2250 rpm where two groups are clearly distinguishable on the dendogram. Next, the dissimilarity matrices are calculated for each listener group. In general terms, the proximity trees for low speeds confirm the numerical observations regarding the accuracy of the filters estimations: the overestimation and the optimum case enable synthesis of similar noises to the measured combustion noise, which validates the use of ESTER for setting the number of extracted components. At 1800 rpm, the same conditions are established, but the noises are less accurate than for the lower engine speeds: the synthesised noises are further away from the reference sound. At 2250 rpm, two listener groups were identified. Their interpretations were completely different, even though the stimuli listened very similar. In order to clarify this point, the specific loudness of the sounds is observed. It allows the exclusion of the three stimuli, thus all the listeners use loudness as a perceptive indicator to separate the different stimuli. Moreover, loudness reveals that there is a frequency band with a difference between the estimations and the reference sound, which corresponds to the low-energy frequency band for the filter. However, the cylinder pressure has a high level of energy in the low frequency range. Thus, the small inaccuracies of the filter below 1.5 kHz become significant errors when synthesising the noise. As a result, the average filter estimation in the low frequencies should be very accurate. Future work will look at identifying the common modal parameters required to obtain a comprehensive filter that will satisfactorily synthesise combustion noise for different operating cases.

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