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# Experimental modeling of Wiener filters estimated on an operating diesel engine

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ABSTRACT

Sound source separation in diesel engines can be implemented using a Wiener filter, or spectrofilter, that can extract the combustion contribution in the overall noise. In this study this filter characterizes the transfer function between a cylinder pressure and a measurement point. An engine is characterized by several filters (one for each cylinder) which are estimated for many operating conditions (engine speed and load). The purpose of this work is to obtain an averaged spectrofilter allowing the synthesis of combustion noise in all operating conditions. This synthesis should be accurate enough to be used in perceptive studies. In order to refine the spectrofilter estimation in the medium frequency band, this paper consists in taking advantage of the multitude of information given by the estimations from different operating conditions. To do this, an experimental model is adopted so modal parameters are extracted from a great number of measured filters. Different procedures such as the ESPRIT method or the LSCE method (modal analysis) are used to decompose the impulse responses on a complex exponential basis. The spectrofilters estimated from different operating conditions are analyzed and compared in this reduced basis, in order to identify the underlying structural parameters. These parameters are compared to the results of an experimental characterization of the stopped engine. The accuracy of the synthesis (number of components of the filter) is an important issue because these filters will be used in perceptive applications, extracting combustion noises.

This paper is an extended version of the work initially presented at the conference Surveillance 6 in November 2011 in Compiègne, France [1] (J. Drouet, Quentin Leclere, Etienne Parizet. Experimental modeling of Wiener filters estimated on an operating diesel engine, in: Proceedings of the Surveillance, vol. 6, Compi‘egne, France, 2011.).



## 1. Introduction

Noise from diesel engines is a major source of annoyance for car passengers and people outside the vehicle. This has led to many studies aiming at reducing this noise, which is partly due to the high pressure combustion in the cylinders, but also to mechanical sources involved in the engine operation (distribution, belts, impacts due to clearances in mechanical joints). It is therefore very important to identify the contribution of potential sources, in order to implement efficient noise reduction solutions. Several studies are dedicated to this issue. First results are obtained from the comparison between different operating conditions: it is shown in [2] how mechanical and combustion contributions to the overall noise are

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varying with operation. Under a certain combustion pressure level, called the critical cylinder pressure level, the noise level does not vary: it means that the mechanical noise dominates the engine noise. Above this limit, the noise level increases linearly in function of the combustion pressure level: the engine noise is thus mainly due to combustion. Another approach, studied in [3], is based on the comparison between the engine operating by itself and driven with an electric motor. The difference between noise levels is considered as the contribution of the combustion. This study shows the benefits of the indirect injection technology over the standard direct injection, concerning the combustion noise reduction. Of course these methods are based on the rough assumption that the mechanical sources are not affected by changes in the loading conditions.

Several papers studied the possibility to use signal processing tools to separate the contribution of combustion in the overall engine noise [4–6]. The idea is to use the coherence between the acoustic pressure outside the engine and cylinder pressure signals, measured using pressure sensors introduced in the cylinders through the cylinder head. However, there is a strong difficulty due to the fact that mechanical excitations are strongly coherent with the cylinder pressure signals, making it difficult to obtain a valuable result. However, this difficulty can be overcome by introducing some randomness in the injection, as shown in [7], but this approach is somewhat intrusive, and not without effect on the engine operation.

The characterization of the transfer between the cylinder pressure and the acoustic pressure outside the engine is not new. Pioneer studies [8] are defining the structural attenuation as the difference between engine noise and cylinder pressure spectra, in decibels (dB). It is shown that this structural attenuation is relatively constant when changing operating conditions, and that structural attenuations of different engines are quite similar. The outcome of these works has been the commercialization of a measurement system called the combustion noise meter [9], which consists of filtering the cylinder pressure by a typical structural response plus an A-weighting curve, to finally give the contribution of the combustion to the overall noise. But this approach does not use any microphone, and the result only gives a relative indication of the combustion noise level, allowing to estimate for instance the effect of some changes in the injection map on the combustion noise. The structural attenuation, as defined here, is a ratio between two power spectral densities, often studied in octave or third octave bands. It gives an estimation of the modulus of the linear filter between the cylinder pressure and the acoustic pressure, averaged in frequency bands. Thus, it does not allow the direct synthesis of the acoustic pressure from cylinder pressures, which is required to consider the separation of mechanical and combustion contributions in the time domain.

Several works are reported in the literature, addressing the issue of diesel engines source separation in the time domain [10,11]. The most convincing studies belong to the family of supervised source separation approaches: the source (cylinder pressures) is measured, and its contribution to the measured output (microphone) is to be estimated. It has been shown quite recently [12–14] how to implement cyclostationarity tools in this context. Suppressing the periodic parts of signals overcomes the difficulty of high correlation between combustion and mechanical excitations [14]. One result of this operation is that filters obtained from random parts of input and output signals are much more stable to changes in operating conditions than filters obtained with raw signals.

The aim of this paper, which is an extended version of the communication [1], is to show how the filters estimated with these approaches can be used to analyze the structural response of the engine in operation. The originality of this work mainly concerns two aspects. The first one is that the spectrofilters resulting from the source separation algorithm are compared to transfer functions measured with an impact hammer, with the engine stopped. It is shown how this comparison can be used to analyze the transmission paths of the combustion noise. The second original contribution is the application of modal analysis approaches (LSCE [15] and ESPRIT [16,17]), aiming to compare filters obtained at different operating conditions in a modal framework.

The first part of this work is dedicated to some general considerations about engine noise sources, and to the transmission paths of the combustion noise. The second part presents spectrofilters obtained from measurements in operating conditions. These spectrofilters are compared to standard impact hammer FRF measurements on the stopped engine. Then, the basic theory of ESPRIT and LSCE is exposed in the third section, highlighting the similarities and differences between these two methods. They are also compared in practice with an application on a synthetic signal. Finally, in the last section, ESPRIT is carried out on the spectrofilters measured in operation, pointing out the limits of the approach.

## 2. Diesel engine noise sources and combustion noise transmission paths

Diesel engines are complex mechanical systems, in which many sources are contributing to the overall noise. There are several ways of classifying engine noise sources. The classification used in this work, shown in Fig. 1, is loosely based on the literature [18,19]. The internal sources are separated into three categories: the combustion, generating high pressure pulses on internal faces of the combustion chamber; the load-independent mechanical sources, whose behavior is affected only by the rotation speed; and the load-dependent mechanical sources, whose amplitude generally increase with the load. For instance inertia loads and distribution (camshaft and valves) belong to the class of load-independent sources, while the injection system (injectors, injection circuit, and high pressure fuel pump) is a load-dependent source. This classification has the advantage of being closely linked to the physical phenomena, but it also has limitations. Some difficulties appear for instance when considering the excitation generated by the piston on the cylinder block, resulting from a combination of the three categories.

This work is focusing on the combustion noise, resulting from the high pressure pulses in the combustion chamber generated by the auto-ignition of the fuel–air mixture. This pressure pulses are distributed on the combustion chamber