Sound Source Localization Analysis in the Combustion Cycle of ICE Powertrains

Claudio Colangeli[1], Jeroen Lanslots[1], Sebastien Paillasseur[2], Karl Janssens[1], Lucille Lamotte[2]

[1] *Siemens Industry Software NV, BE-3001 Leuven (Belgium). E-Mail:claudio.colangeli@siemens.com*
[2] *MicrodB, FR-69134 Ecully Cedex (France).*

Abstract

Noise optimization of powertrains usually occurs in the late stages of their development cycle. This exposes the manufacturer to the risk of detecting non- optimized noise contributors, causing sound problems which are difficult to be solved when the design process is already too advanced. Sound source localization techniques, supported by advanced processing tools, enable to front-load the powertrain noise assessment, speeding up the development cycle. The application of a cyclic Wiener filter relying on reference cylinder pressure sensors, effectively breakdown the microphone array data into a combustion component, related to the thermal activity occurring in the Internal Combustion Engine cylinders, and a mechanical component originating mainly from auxiliary systems in the powertrain such as water pumps, air conditioning units, alternators, etc. Sound source localization on these separated components allows to identify the main sources related to combustion and mechanical noise contributors. The powertrain - mechanical and/or combustion - noise can also be analyzed in segments of the combustion cycle itself. This requires a pre-processing in the angle domain, first, after which sound source localization is applied on angular ranges. This paper describes these methodologies, their synergies and their application on engine test bench experimental data to prove their industrial exploitability.

Introduction

The combined use of combustion/mechanical noise breakdown and angle domain Sound Source Localization (SSL) allows the accurate identification of the noise contributors related to the combustion phenomena, enabling to locate them within the operating cycle of the Internal Combustion Engine (ICE). At the same time, a similar analysis can be carried out on the residual part of the total contribution in order to assess mechanical phenomena such as: belt, auxiliaries, manifold vibrations, etc. These latter noise contributors will be generically identified in the paper as "mechanical noise". After an introduction of the theoretical principles on which combustion/mechanical breakdown and Angle Domain SSL are grounded, we will report on an experimental application case of an ICE test bench in which the combination of the proposed pre-processing methods (**Figure 1**) allows a clear identification of the main combustion and mechanical noise contributors.

Theoretical principles

Combustion/mechanical breakdown

The decomposition of measured acoustic signals into a "combustion" and a "mechanical" part proposed in this paper is based on the Cyclic Wiener Filtering technique described in references [1], [2] and [3].

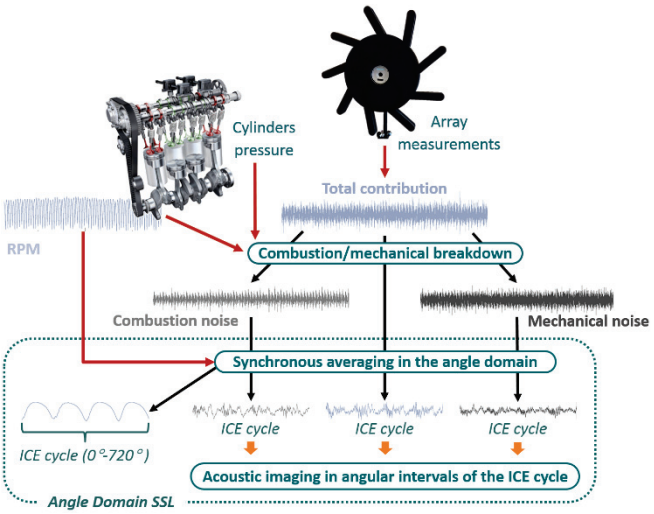

Figure 1: Combustion/mechanical breakdown and Angle Domain SSL can be combined for advanced ICE powertrain noise analysis.

Wiener filtering is used to estimate a reference process by linear time-invariant filtering from noisy observed data. In the case of "combustion noise" separation, the filtering process retrieves the coherent part of the microphone array signals with a cylinder pressure signal. Such approach can be generalized to the separation of any noise contributor, provided the availability of a suitable reference signal.

A Wiener filter is obtained by computing the H1 transmissibility estimator based on input (cylinder pressure signal) and output (microphone signal) auto and cross spectra. The Cyclic Wiener Filtering method is therefore an extension of the classical formulation, based on the assumption that the measured signals are cyclo-stationary. This implies that the estimation of the transmissibility functions should account for the periodicity of the reference and response signals. The computation is therefore performed by averaging the sought input/output relations over multiple realizations of the machine's operating cycle. Such relations between the cylinder events and the microphone array response are at each realization computed within angular windows synchronized with each cylinder firing. These windows are replicated with a period that equals an engine cycle (720° of the crankshaft in the case of a 4 stroke diesel engine, see **Figure 2**).

The application of the designed cyclo-stationary Wiener filters allows the separation of the "combustion part" from the total noise contribution. The residual part can be obtained by subtraction of the just retrieved contributor.

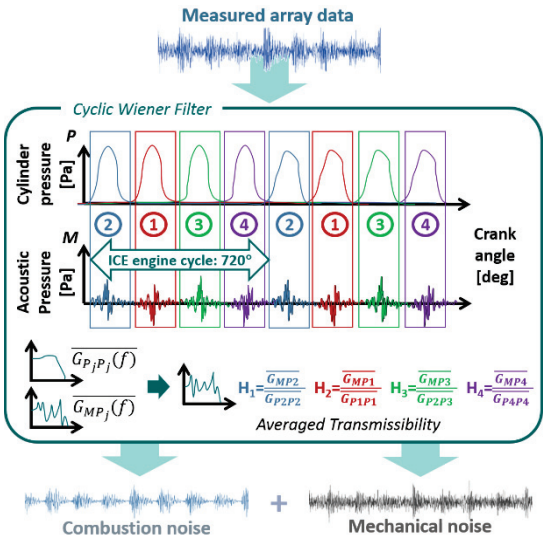

Figure 2: The combustion/mechanical breakdown algorithm relies on the construction of Cyclic Wiener Filters based on the coherence between the array measurements and the cylinder pressure signals.

Angle Domain Sound Source Localization

Angle Domain SSL consists in performing acoustic imaging on array data which are processed by "synchronous averaging". This processing makes it possible to obtain an acoustic map reporting the noise sources at any instant of the operating cycle of an engine. Similar approaches have been used for condition monitoring of rotating machinery and some examples are reported in [4] and [5].

Given a microphone array dataset, the proposed algorithm requires the knowledge of the rotational speed of the element on which to focus the analysis. In the case of powertrain testing – therefore also in the example reported in this paper – such rotating element is the crank shaft of the engine.

The Angle Domain SSL algorithm works as follows:

1) *Resampling of the measured quantities from time to angle domain*. This operation is made possible by the knowledge of the angular evolution of the crank shaft within the ICE cycle.

2) *Averaging quantities in the angle domain.* Multiple realizations of the operating cycle of the ICE are averaged in order to retain the cyclo-stationary component of the measured quantities (in particular: array data and rotational speed).

3) *Selecting an angular segment.* This is obtained by gating the averaged cycle obtained at step 2) in the wanted angle interval.

4) *Resampling from angle to time domain.*

5) *Acoustic imaging* of the selected segment.

The method, therefore, consists in a pre-processing of the array data through synchronous averaging followed by a beamforming analysis on short time traces transformed back in the frequency domain. The interested reader can find further details about the algorithm and its main advantages and limitations in Chapter 5 of reference [6].

Application on an ICE test bench

The two methods (combustion/mechanical breakdown and Angle Domain SSL) potential are hereafter shown on an ICE test bench experimental case carried out on a 4 cylinder diesel direct injection 1.9 l engine (**Figure 3**). In order to enable the proposed pre-processing of the acquired array data, the engine test bench was equipped with 4 cylinder pressure transducers – one per cylinder – and a 60 ppr angle encoder to measure the rotational speed of the crank shaft.

(a)

(b)

Figure 3: The experimental setup. *(a)* The LMS HD Acoustic Camera – 54 microphones – is placed 30 cm far from the engine. *(b)* Image of the engine taken by the embedded camera.

In the example reported in this paper the ICE is running at the nominal speed of 1200 rpm. **Figure 4** reports an example of acquired microphone signal – "Total Contribution" – , the computed rotational speed evolution – "RPM" – and the result of the combustion/mechanical breakdown in time domain.

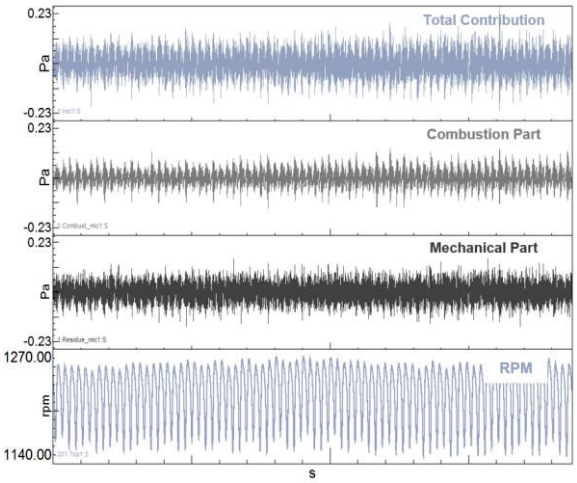

Figure 4: Combustion/mechanical breakdown results in time domain. In the example reported in this paper the ICE is running at the nominal speed of 1200 rpm. Fluctuations of the rotational speed are visible in its time trace.

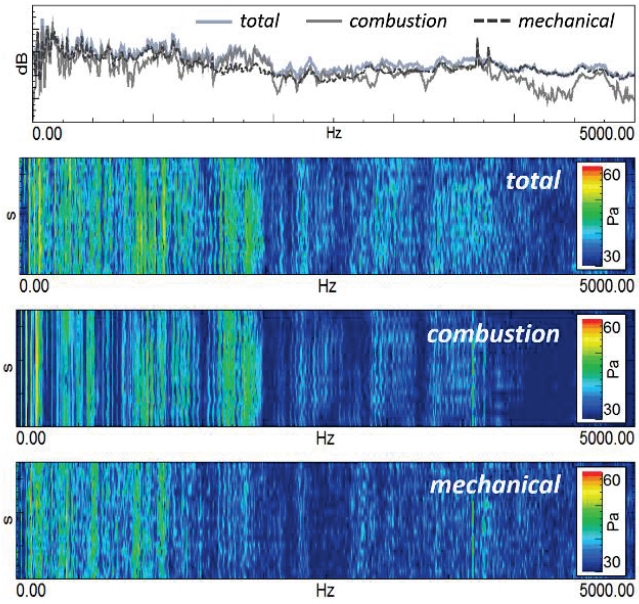

Figure 5: The frequency analysis of the measured (*total*) and computed (*combustion* and *mechanical*) signals reveals that, despite the presence of the engine orders, combustion and mechanical noise assume similar levels up to 1500 Hz. Combustion noise is dominant in the range 1500 – 2000 Hz, while the mechanical noise contributor is prominent for frequencies higher than 4000 Hz.

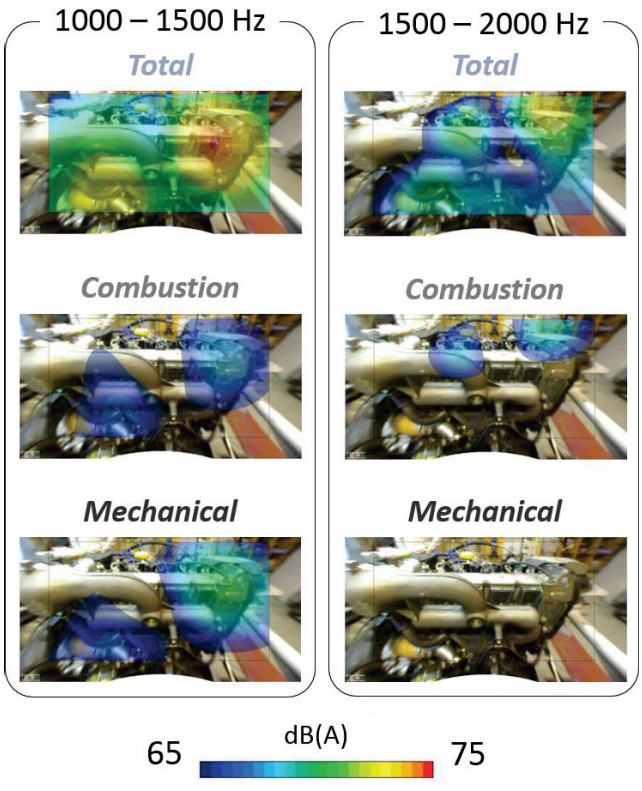

Figure 6: Sound Source Localization results computed in the frequency ranges of 1000 – 1500 Hz and 1500 – 2000 Hz respectively on the *"Total"* array data and on the *"Combustion"* and *"Mechanical"* contributions obtained through combustion/mechanical breakdown.

The acoustic imaging results, computed respectively adopting the total contribution to the array response and its decomposition into combustion and mechanical noise components, confirm the frequency analysis depicted in **Figure 5**. In the frequency range 1000 – 1500 Hz the *"Combustion"* and *"Mechanical"* contributions are comparable in levels and in source distribution. The major source is located in the region of the engine *belt*, higher in level in the *"mechanical"* contribution acoustic image. Combustion noise dominates the frequency range 1500 – 2000 Hz in which the SSL results reveal the *"Total"* contribution to be composed by sources located in the cylinders area of the engine (*"Combustion"* acoustic image). The *"Mechanical"* noise contributors are, in this frequency range, below the dynamic range of the reported images (**Figure 6**).

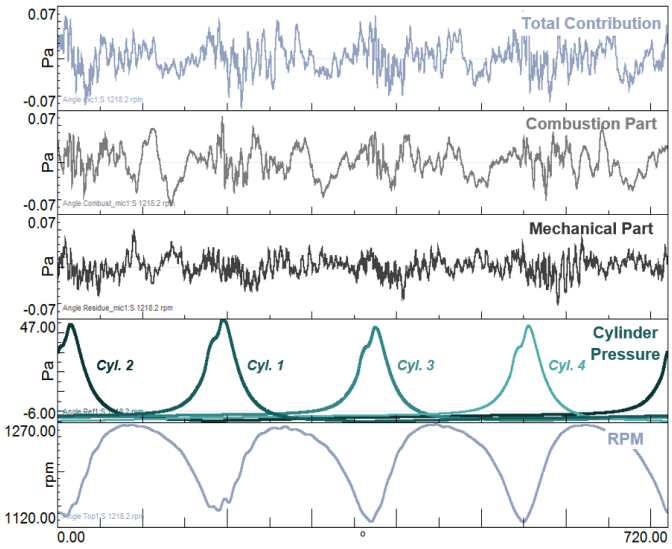

Figure 7: Synchronous averaging results on the studied experimental case.

The synchronous averaging performed in the angle domain, over the multiple realizations of the ICE operating cycle, allows to preserve the cyclo-stationary part of both the total and partial contributions (**Figure 7**). The computed signals reveal 4 patterns – particularly distinguishable in the cases of "Total Contribution" and "Combustion Part" – triggered by the cylinder firings. Such impulsive events are also responsible for the order-2 fluctuations of the rotational speed ("RPM" signal) of the crank shaft. Angle Domain SSL, performed on the signals reported in **Figure 7**, identifies transient noise contributors within the ICE cycle. Interestingly, the firing event does not only generate a single source in correspondence of the cylinder location: it also implies the appearance of additional sources due to the vibrations of the entire engine block (**Figure 8**).

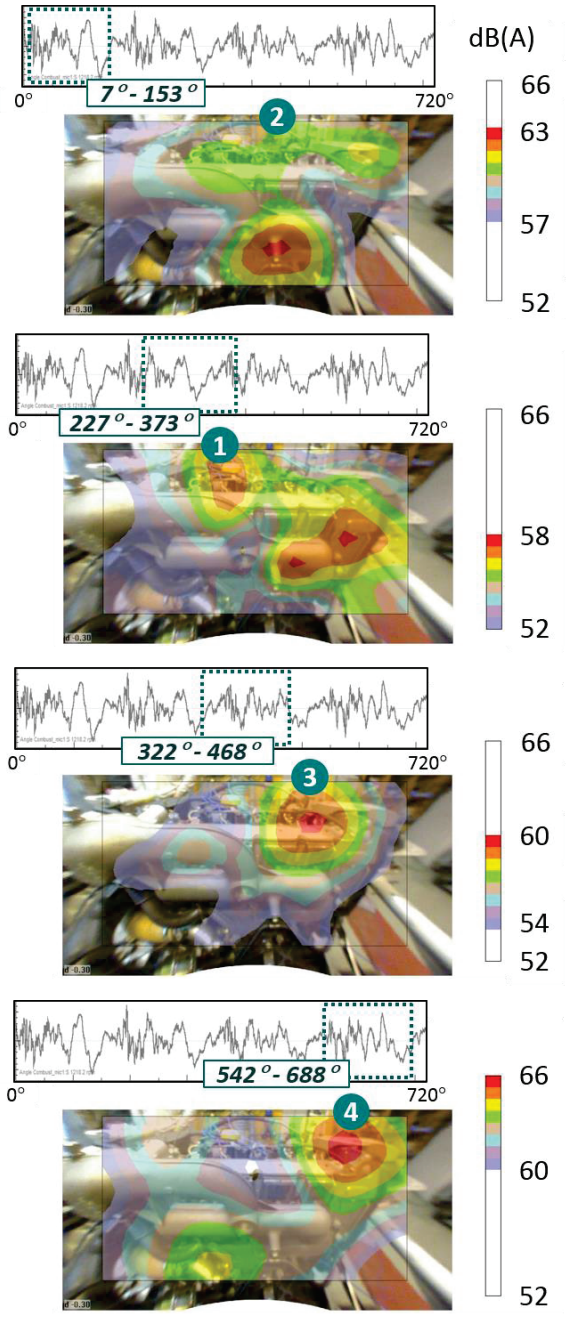

Figure 8: *"Combustion"* noise acoustic images computed in the frequency range 1000 – 3000 Hz and within the angular interval – of 146° – corresponding to the firing of the four cylinders (sequence: 2, 1, 3, 4). For the sake of clarity of the pictures, the acoustic images have been reported with an optimized scale within 6 dB. The scale is not fixed for the four images because of their large difference in levels.

While the *"Combustion"* noise sources distribution evolves along the ICE operating cycle, in relation to the cylinder firing sequence, the analysis of the *"Mechanical"* noise reveals the persistent presence – during the entire ICE cycle – of the *belt* noise source. An example of such noise contributor's acoustic image is reported in **Figure 9** in the angular range: 87°-233°. A second noise source appears in correspondence of the engine manifold. Such phenomenon is only observed in the angular interval: 154°-300°.

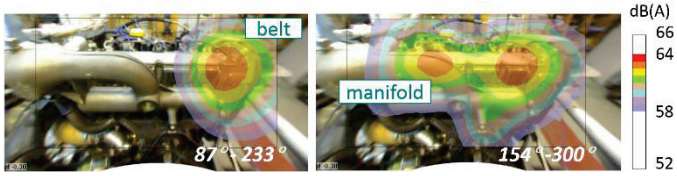

Figure 9: Examples of *"Mechanical Part"* acoustic images in the frequency range 1000 – 3000 Hz.

At higher frequencies the acoustic scene is dominated by "mechanical" noise contributors. Results reveal noise sources located in the region of the engine *belt* and in the one of the intake/exhaust *manifold* (**Figure 10**).

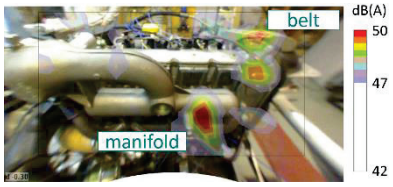

Figure 10: Example of *"Mechanical"* noise acoustic image calculated in the frequency range 2500 – 4000 Hz and in the angular interval 461° – 607°.

Conclusions

The combined use of combustion/mechanical noise separation and angle domain SSL allowed the identification – and their location within the operating cycle – of the main noise sources of an ICE. The reported analysis could be further detailed by separating additional noise contributors such as intake/exhaust noise by properly adding reference sensors to the measurement setup. Furthermore, we aim at improving the affordable spatial resolution and pursuing the identification of correlated as well as uncorrelated sources adopting inverse acoustic imaging methods instead of direct approaches.

References

[1] J. Antoni, B. Boustany, F. Gautier, S. Wang. "Source Separation in diesel engines with the cyclic Wiener Filter". *Euronoise Conference, 2006.*

[2] Lanslots, J.; Janssens, K.; Minck, O.; & Lamotte, L. "Application of noise separation techniques on sound source localization". *In INTER-NOISE and NOISE-CON Congress and Conference Proceedings (Vol. 2012, No. 5, pp. 6481-6491).*

[3] Bianciardi, F.; Janssens, K.; Gryllias, K.; Delvecchio, S.; et al. "Assessment of Combustion Mechanical Noise Separation Techniques on a V8 Engine". SAE Technical Paper 2017-01-1846, 2017, https://doi.org/10.4271/2017-01-1846.

[4] Antoni, J.; Abboud, D. & Xin, G. "Cyclostationarity in Condition Monitoring: 10 years after". *ISMA Conference, 2016.*

[5] Cardenas Cabada, E.; Hamzaoui, N.; Leclère, Q. & Antoni, J. "Acoustic imaging applied to fault detection on a rotating machine bench". *ISMA Conference, 2016.*

[6] Colangeli, C.; "Clustering Inverse Beamforming and multi-domain acoustic imaging approaches for vehicles NVH". *PhD thesis, Università Politecnica delle Marche, 2017.*