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ARRAY BASED ACOUSTIC POWER MEASUREMENT, RENAULT PASS-BY NOISE

[1] Minck, Olivier; [1] Le Magueresse, Thibaut; [1] Lamotte, Lucille*; [2] Locqueteau, Christophe; [3] Bouvet Pascal
[1] MicrodB, France; [2] Renault, France; [3] Vibratec, France

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ABSTRACT –

European new standard regulation (UN ECE R51-03) will command to car manufacturer to decrease pass by noise levels of their cars. In that context, Vibratec, Renault and MicrodB, part of a 10 companies research project, have decided to launch the ECOBEX project [1]. The global objective is to propose breakthrough solutions in order to design acoustic treatment of the engine. The experimental characterization of acoustical sources generated by the engine is a preliminary requirement to achieve the project objective. The work leaded by MicrodB aims at getting accurate localization and quantification of the sources on chassis dyno bench, and engine test bench. The proposed method called "patch measurement" is based on the sequential measurement of acoustic field around the engine moving the array of microphones. The first technical challenge is to obtain a fully synchronized signal for each microphone from this patch measurement. Then, the estimation of the microphones position relatively to the mesh of the tested object represents the second difficulty. The third challenge is to use the proper propagation acoustical model that are mandatory for quantitative source estimation. Finally, the last task is to correctly compute the radiated intensity on the 3D mesh. This paper will describe at first the methodology used for all these steps and it will present the results obtained during the ECOBEX project.

INTRODUCTION

The new European standard (UN ECE R51-03) introduces a new procedure for pass by noise measurement, in addition to a decreasing value for the noise level over years. This will lead to reduce the pass by noise by 4dB in the coming 8 years. Considering this 4dB decrease, 97% of the actual cars became non-conform. In this context, Ecobex project has been created in 2014. It consists in a French project, funded by the Government and the regions, and includes 9 companies around Vibratec (leader): Renault, RJP, MECAPLAST, Isover, CrittM2A, Utc, Matelys, Esi and MicrodB. The goal is to develop an optimized engine acoustic package to reduce the engine contribution at a compatible level with the contribution reduction on other sources, and while following constrains like cost and mass for realistic mass production. The methodology adopted targets to experimentally characterize the engine as a noise source to feed a simulation software for the prediction of the effectiveness of acoustic shields on the exterior noise.
The work package presented in this paper describes the engine characterization. In a first part, the methodology for efficient measurement of the 3D sound field around an engine will be presented, then the post processing approach with validation on mockup will be detailed, and finally some results on the real engine will be presented.

MEASUREMENT METHODOLOGY

Patch measurement

Measuring the 3D sound radiation around the engine requires sensors to be deployed around it. To achieve this, different experimental set-ups may be used:

- Pressure sensors set as described in the standard (ISO 3746 / ISO 3744) for power estimation of the object. This has the major drawback of giving the overall power level with no information on the source localization on the object;
- Intensity probe measurements as described in ISO 9614-2, but maximum detail that may be obtain is the face ranking, and global sound power;
- Array measurement and computation of the intensity directly on the mesh, which is the most detailed analysis that can be obtained, and such analysis may be reused for simulation. This is the chosen analysis.

For array measurement, as a synchronous signal is required between microphones, the ideal case would be to set a huge number of microphones around the engine, and measure the field in a single recording. But such a system able to give results up to 6 kHz would require hundreds of microphones with frontend, and then incur a high cost.
A patch measurement approach has been preferred, as it only needs a single microphone array (HDCam 54 channels version). The experimental procedure involves moving the array around the object of interest. A pre-processing step is required to then obtain a fully synchronized cross spectrum matrix (CSM). Using fixed reference sensors makes possible, like described in [2] to compute the complete CSM by using phase with references.

The global CSM (S_{MM}) is computed using: $S_{MM} = S_{RM}^{H} S_{RR}^{-1} S_{RM}$

With:

- S_{RM}^{H} the measured Hermitian matrix of cross spectrum between reference sensors and array microphones,
- S_{RR}^{-1} The pseudo-inverse of reference cross spectrum matrix.

Quality of synchronization will be strongly dependent on the quality of the inversion of the S_{RR} squared-matrix. The chosen strategy is thus to decompose the matrix into principal components. For each component, a virtual S_{MM} matrix is estimated following the aforementioned equation. The number of principal components to keep is evaluated by minimizing the error between measured cross spectrums (on each single array position), and computed cross spectrums. In a final step, the computed global CSM will be modified with the measured cross spectrum of each position. Figure 1. Full Cross spectrum matric presents the measured, computed, and final CSM for the patch measurement.

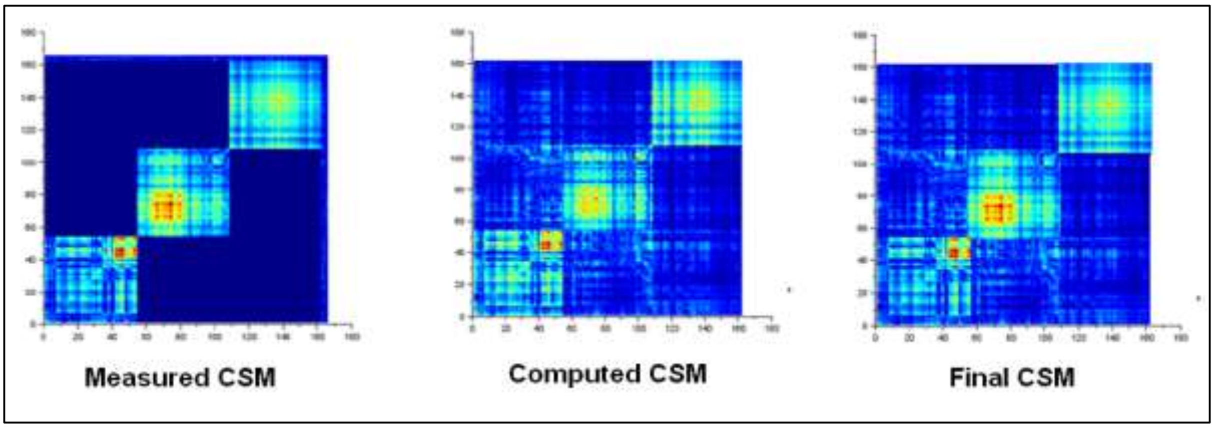

Figure 1. Full Cross spectrum matrices

Geometrical definition

Patch measurement requires the displacement of the array around the engine, and any kind of sound source localization method needs the fine knowledge of the microphone positions in the space relatively to the object of interest. To overcome this difficulty, MicrodB has used a positioning probe based on the time of flight, ensuring an accuracy of around 1mm. It allows a fast measure of the change of basis from the array microphones axis to the mesh axis system. Figure 2 presents the positioning tool and the resulting mesh with multiple positions of array displayed in colors.

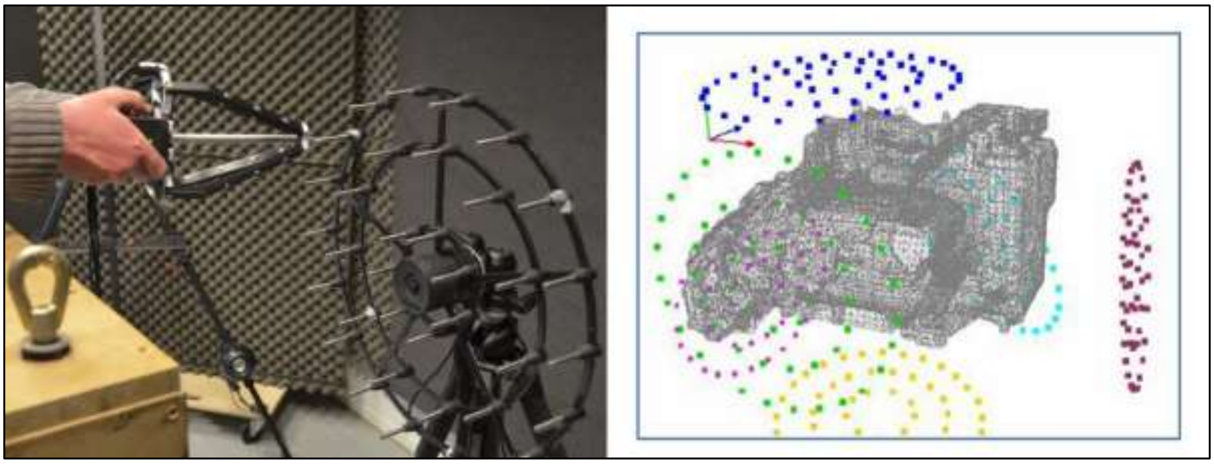

Figure 2. Positioning device (left), and mesh example with array setup (right)

Transfer functions estimation

Once the geometry is known, transfer functions between point sources positioning on the mesh and the sound pressure measured by microphones may be estimated. It is really often done using free field assumption (green formulation). But such approximation doesn't take into account scattering and reflection due to the object presence. In terms of localization of sources on an engine for example, the resulting hologram would present sources with very loud "ghost sources", and wrong source amplitudes. The free field assumption is less a problem when considering simple faces of the object, in an anechoic chamber, and if the main source is actually on the currently measured face.

A second approach to get the transfer functions would be to measure them. But this is easy to understand that measurements to get a bandwidth up to 6 kHz, so with a mesh composed of 5000 nodes, would take a very long time, and it would require a heavy data management. A third approach would be to use FEM or BEM simulation software, that has been successfully tested at MicrodB [3], and shows a good increase in the stability of the results. However, this is often not so simple to prepare the mesh, import microphones positions, run the simulation for high frequency, and then import the results in the testing software. A forth approach may be to integrate an algorithm able to estimate these transfer functions. This has been develop during T. Le Magueresse PhD at MicrodB[4]. This method is based on equivalent source modeling (ESM) [5], adapted for transfer functions calculation, and with the following assumptions:

- Radiating object is rigid (normal velocity of nodes on the mesh is null);
- Sommerfeld radiation condition.

The propagation of waves around a rigid sphere has been studied to first validate our approach. As this is a well-known study case, comparison will be done between Sphere Related Transfer functions (SRTF) and the one obtain using ESM. Figure 3 presents the module and the phase of the FRF calculated by the free field assumption (in blue), by the ESM method (in red) and by the analytical expression of the SRTF (in black) between a source placed outside the sphere and a reception point placed on the sphere.

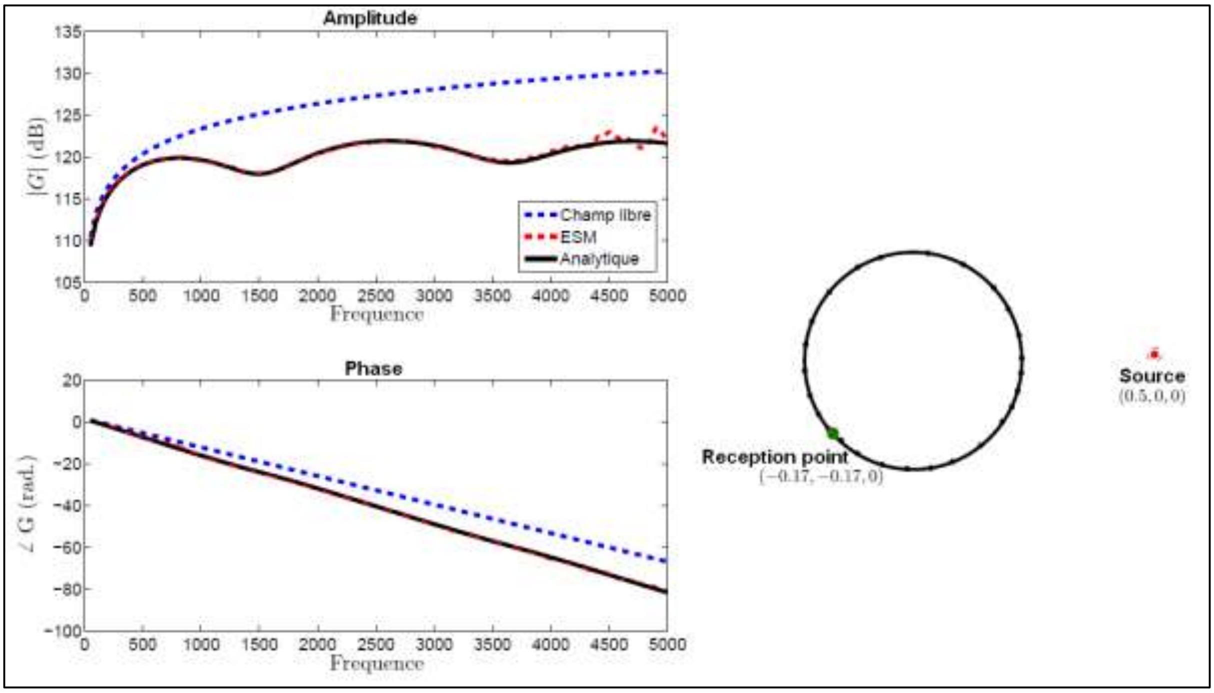

Figure 3: Numerical validation of ESM applied to rigid sphere case. Blue is free field result, red is ESM result, black is SRTF result (reference)

ESM algorithm shows a really good behavior, and especially for amplitude of the transfer function, it would increase capacity of algorithm to achieve correct quantification on such a case.

Another validation has been done using a wooden engine mockup. Figure 4 presents the mockup, and the setup. Simulation will be compared to direct measurement of the transfer function.

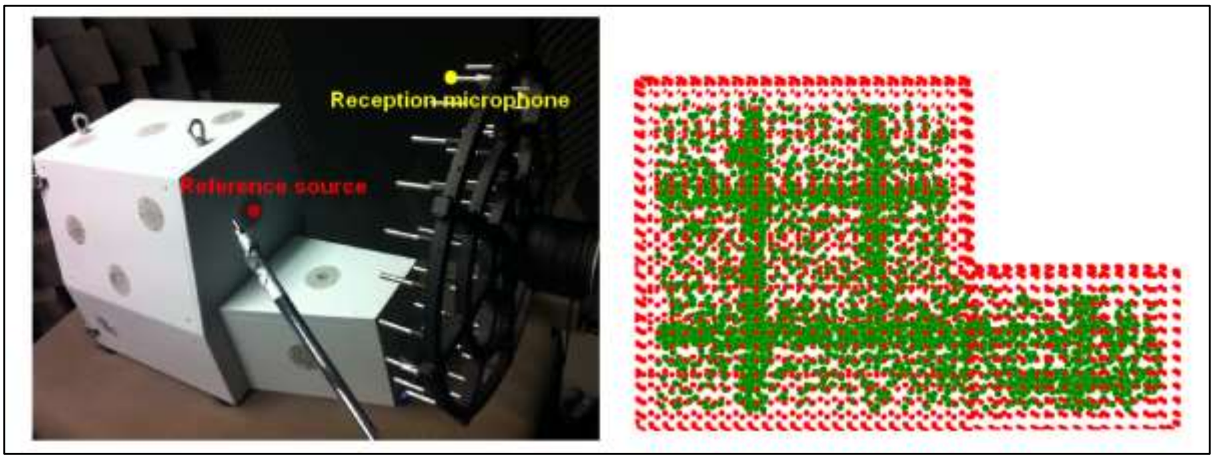

Figure 4. Engine mockup, and test setup ((left); Numerical model with equivalent source in green color (right)

The Figure 5 is the comparison of the transfer function obtained by the measure, the equivalent source method (ESM), and the free field approximation. At first on the amplitude, the ESM gives better results than free field from 500 Hz, and gives much accurate values after 1 kHz.
The phase estimation is also improved a lot. As the phase between microphones is a very important parameter for the localization and quantification, the simulated transfer functions will then allow post processing algorithms to have a lower uncertainty.

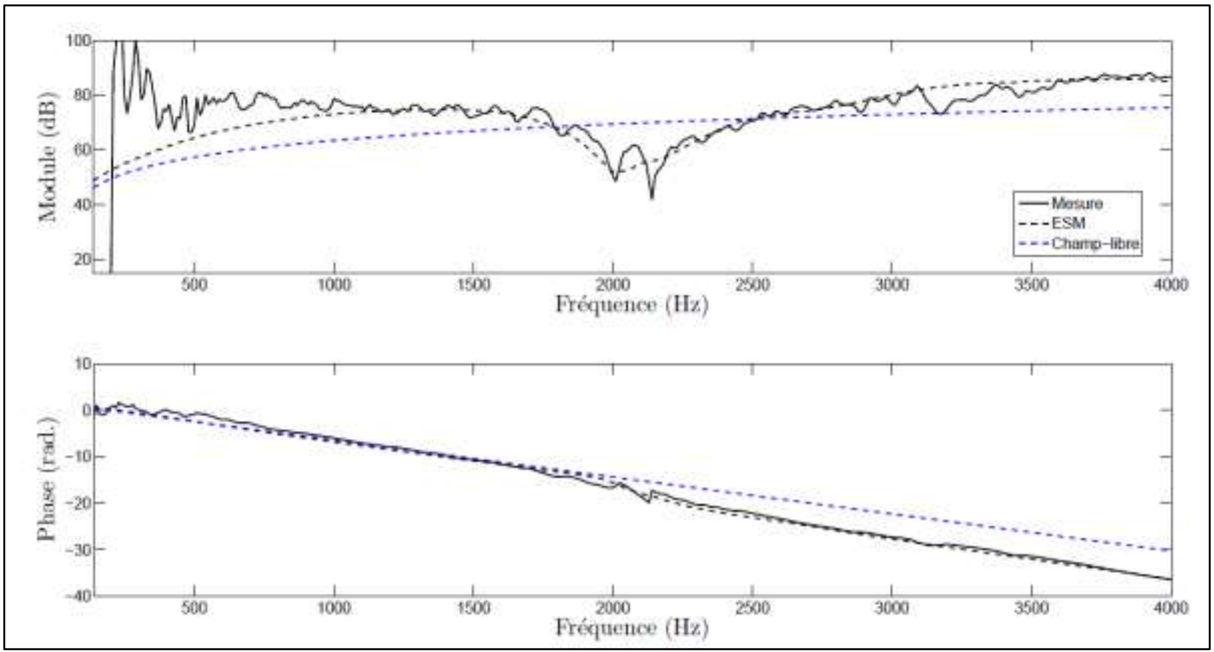

Figure 5. Module and phase of the transfer function (setup fig 4), measured (solid black), simulated with ESM (dotted black), and free field (dotted blue).

Great advantage of this ESM algorithm for transfer function simulation, is that the same mesh may be used than post processing computations. It means that no complex import/export operation is required, and this step is integrated into the global software for quantitative analysis.

POST PROCESSING

Generalized Acoustic Holography (GAh)

Knowing both the propagation model given by the transfer function and the synchronized array measurements, it is possible to deduce the amplitude level and the position of sources on the mesh of the engine. Many methods exist in the literature to reconstruct sources field from array measurements. Nearfield Acoustical Holography reconstructs the sound field using the plane wave decomposition, Helmholtz Equation Least Squares (HELS) using the spherical harmonics decomposition, to mention just a few of existing methods. It has been shown that all of these methods can be generalized using a probabilistic approach in a simple 2D set-up [6] or in a complex 3D shape structure [5]. This probabilistic approach combined with the procedure explained above concerning estimation of the transfer function define the Generalized Acoustic Holography (GAH). Further information about probabilistic models of the noise and the unknown sources can be found in references [5,6]. The method offer a solution describing the source distribution on the mesh which minimize both the least square error (residue) and the stability of the solution in terms of energy, which leads us to minimize the following cost function:

$J(q) = |Hq - p\,|^2 + \lambda||q||^2$ (2)

With :

- H the transfer function matrix describing the acoustic propagation from each source placed on each node of the mesh to each microphone of the array. This matrix has been constructed using the ESM method presented above;
- q the unknown vector complex amplitudes of point sources placed on nodes of the mesh;
- p the complex pressure calculated from the whole re-synchronized CSM;
- λ the regularization parameter computed by Bayesian approach [6].

The minimization of the cost function of the equation (2) brings us to the well-known Tikhonov solution:

$q = H^*(HH^* + \lambda^2 I\,)^{-1}p$ (3)

Once the estimation of volume velocities of the point sources is available, the projection on the 3D mesh is done and makes possible to localize acoustical default and to quantify sound power by zones of the mesh.

APPLICATION TO ENGINE AND CAR FRONT

Engine test setup

The tested engine has been installed in a full anechoic chamber at CRITT M2A, and some specific running conditions has been selected. It consist in stationary configurations for different engine speed, and gearbox ratio engaged, selected from the run-up tests of the new standard. All the engines faces will be measured for the selected engine speed / gearbox ratio, and also for idle state. Figure 6 shows the installed engine, and the 5 different positions of the array measured (virtual array of 270 microphones). 8 reference microphones has also been measured for synchronization of positions.

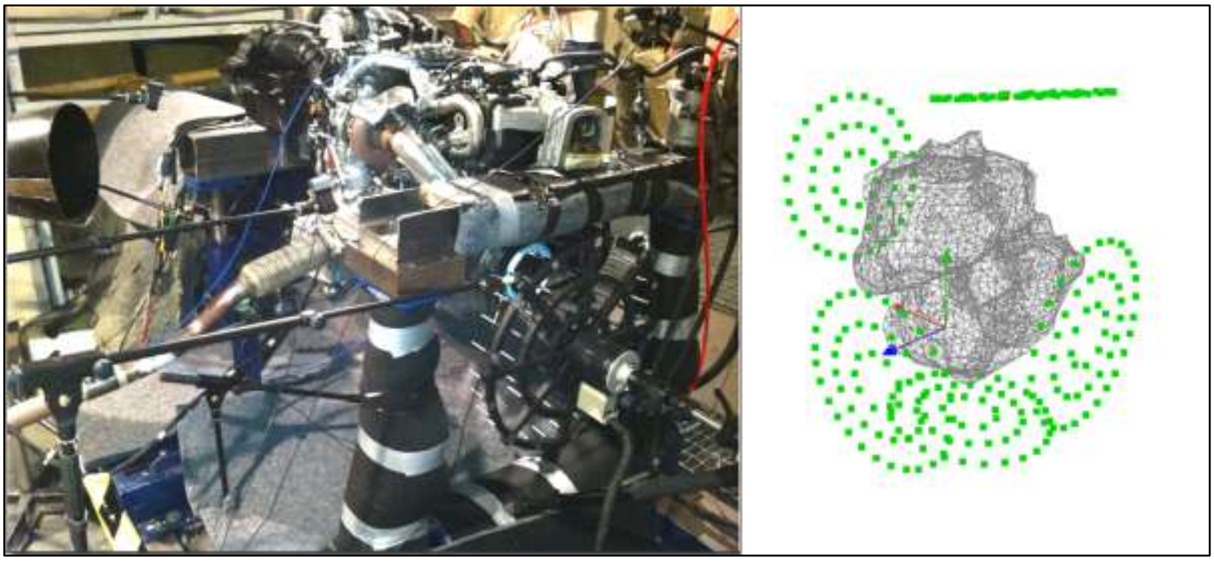

Figure 6. Engine in the test cell (left), mesh with the measured array positions (right)

As the transfer functions simulation will contain only the engine mesh, and nothing about the standing structure, all the beams of the bench has been covered with acoustic material to avoid reflections. Figure 7 is an example of the hologram obtain for a frequency of 2 kHz for the maximum torque, third gear, and a selected engine speed. The localized area correspond to the oil pump embedded in the engine body.

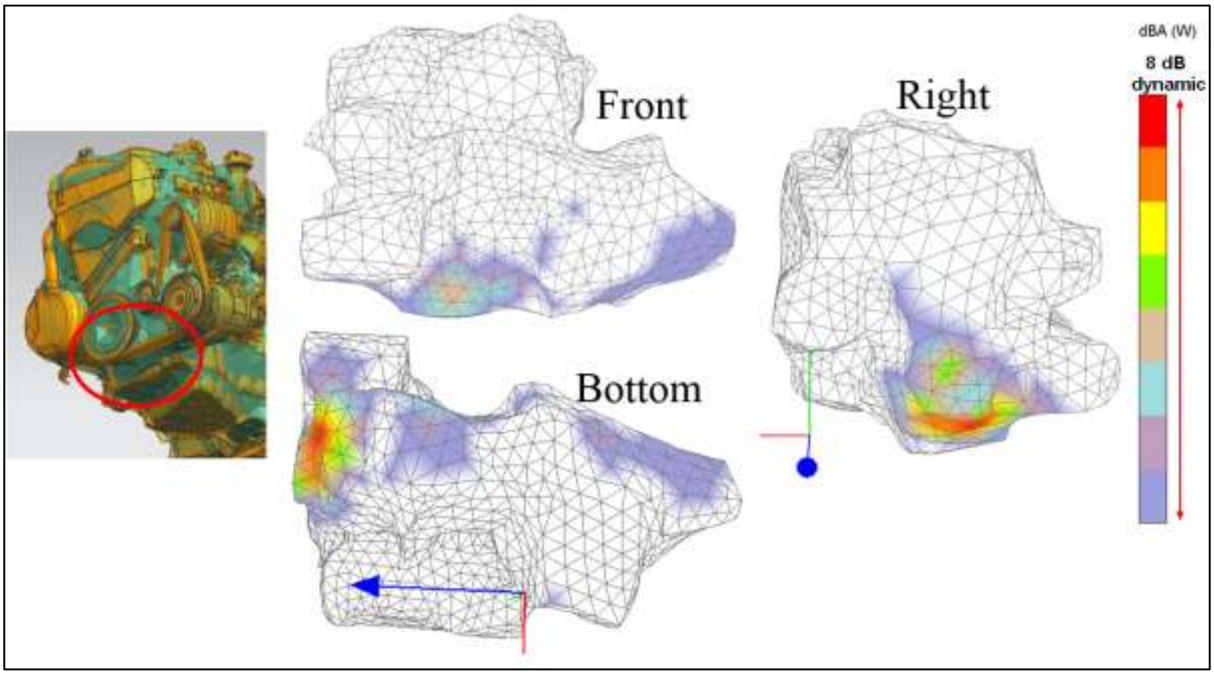

Figure 7. Intensity hologram at 2 kHz for different faces view, full torque, third gear.

The following step will be to integrate the full result in a simulation software able to analyze radiation of the engine installed in the car, and to run optimization of the acoustic package.

In order to validate the acoustic power levels computed with array measurement, an additional test with intensity probe measurement has been done for idle state, and partial torque with fourth gear engaged. Power determination using intensity probe has been done following the ISO 9614-2 standard, and the practical measurement is done with a scanning over the surface of each faces. The standard gives an error range of 2dB with used intensity probe and scanning method. Figure 8 shows the comparison, and accuracy of the array based method stays within 2dB from the intensity based measurement.

This 3D intensity hologram presents lots of advantages:

- Analysis is much easier because it is display on the mesh, and doesn't need the comparison of 2D faces hologram [7],
- It is possible (and has been done for EcobeX project) to export intensity on each node as function of the frequency, and use it in simulation software.
- A function to select components, or sub-area, directly on the mesh is available [8], and allow the user to define its own zones to obtain a reliable ranking of them.

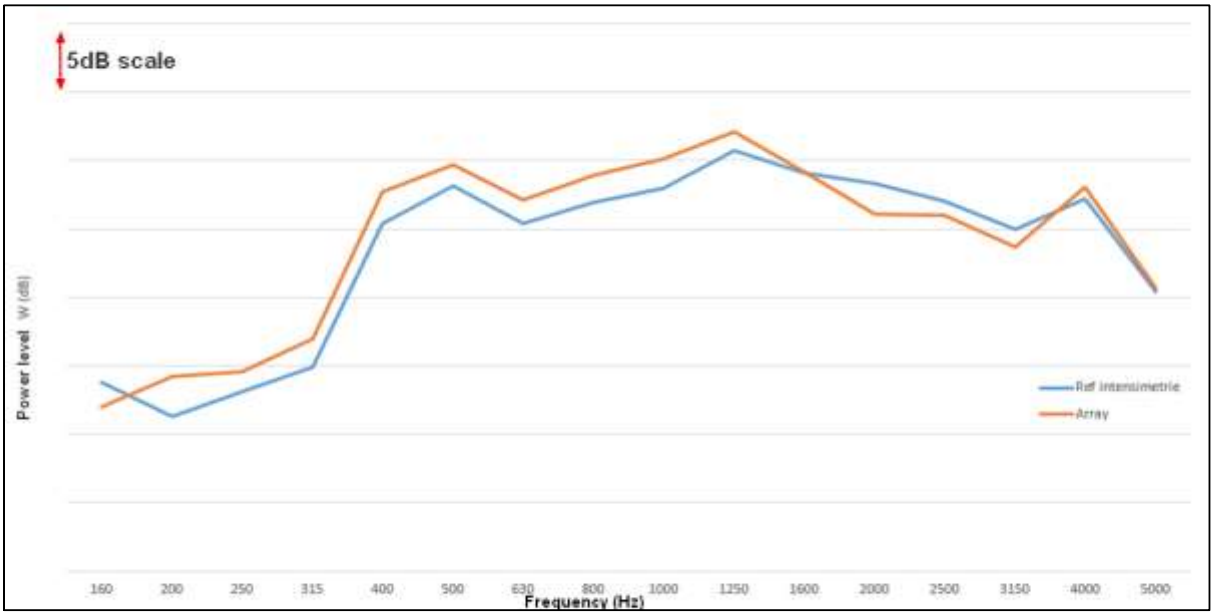

Figure 8. Power level comparison, partial torque-4th gear, between intensity probe (blue), and Generalized Acoustic holography (orange)

Car front setup

The car has been installed on a dyno bench with semi-anechoic chamber at CRITT M2A, and same running points has been measured than for the engine bench testing. The array has been moved around the front of the car over 5 positions (virtual array of 270 microphones). Figure 9 shows the car on dyno, and the mesh with used array positions.

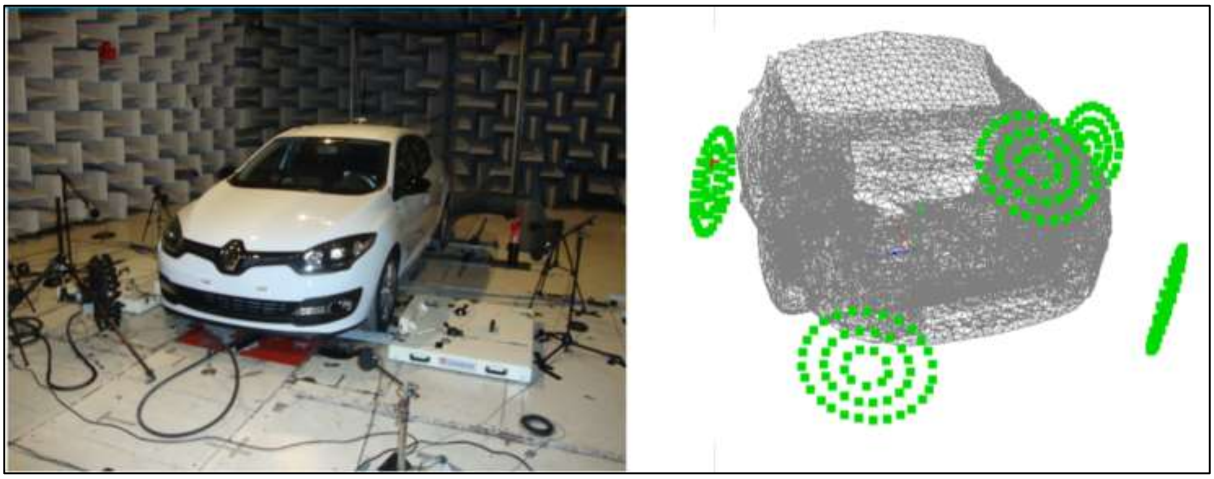

Figure 9.Car on the dyno (left), mesh with the measured array positions (right)

Transfer functions are once again simulated with the equivalent source method, then power computation is done on the mesh presented on Figure 9.
To compare the results with a reference, a power measurement has been done by CRITT M2A in a reverberant room for the car in idle state. The results will be compared with the array based method in Figure 10. The error compared to reverberant room stays below 3dB for the full frequency range.

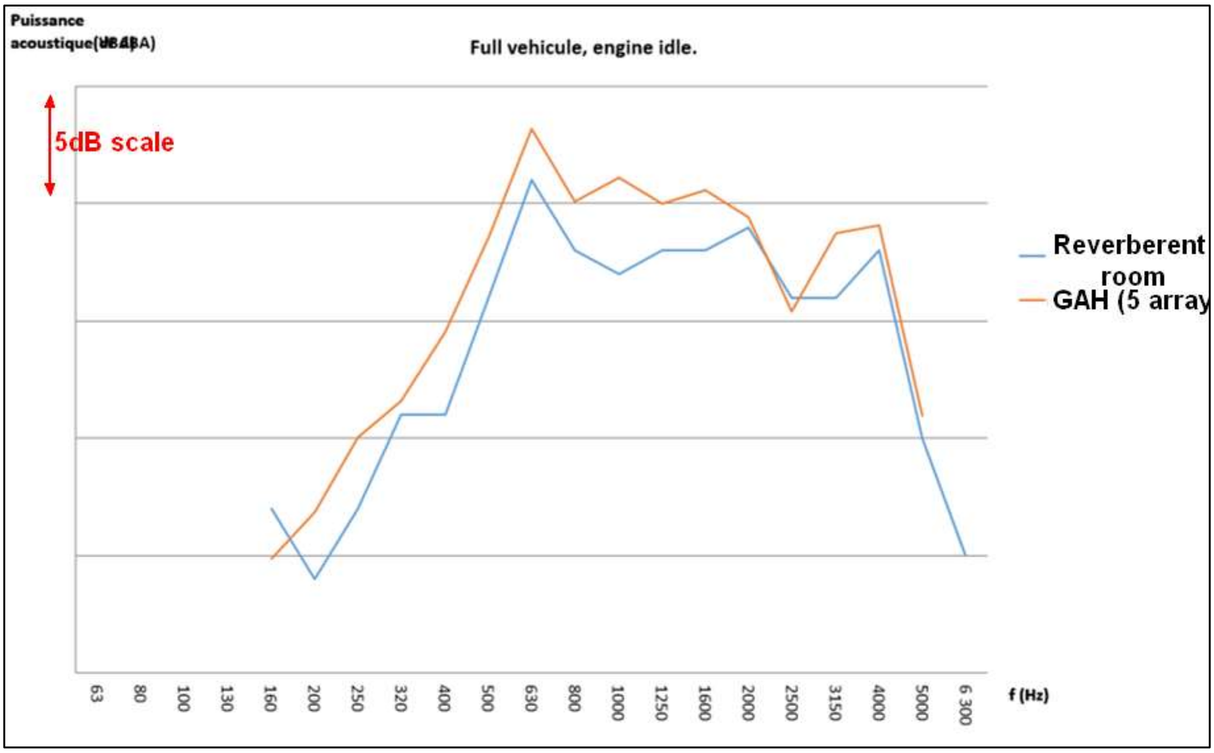

Figure 10. Power spectrum comparison, full car, idle state, measured in reverberant room (blue), and with generalized acoustic holography (orange)

Once validity of the results is clear, hologram may be used for the analysis of weak parts of the car. One example of hologram is given in Figure 11, and it contains lots of information. At first, the right side of the car radiates more energy, and this results is to be considered with the result in the engine bench that shows more source on the right side of the engine. Some energy is radiated through the wheel, through the front air inlet, and from the bottom of the car reflected on the ground.

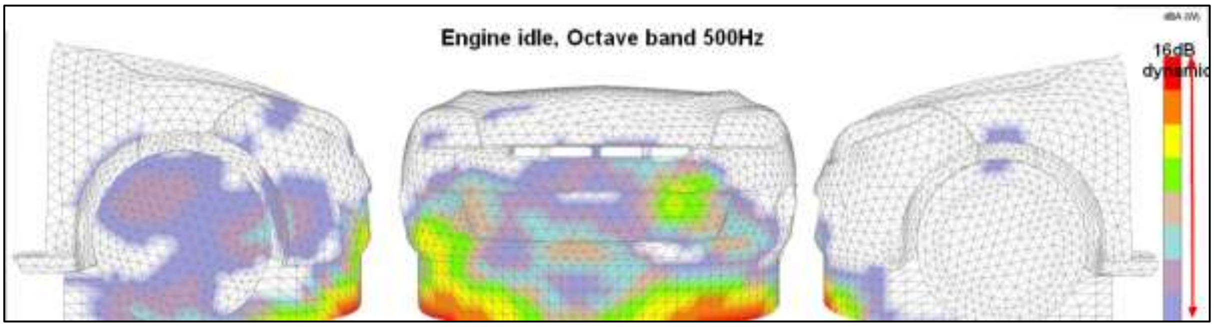

Figure 11. Intensity hologram for octave 500Hz, engine is idle, right face (left), front face (middle), left face (right)

These results will be used by other companies to validate the simulation software, and working on the shields to start operational definition of package.

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