

# An Update and Comparative Study of Acoustic Modeling and Solver Technologies in View of Pass-By Noise Simulation

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## ABSTRACT

As the legislation for pass-by noise (PBN) has recently become more stringent, car manufacturers face again a challenging task to reach the new SPL objective (70dB(A)). A good design of the engine bay is therefore required to sufficiently attenuate the noise coming from sources as the engine and the intake. This involves proper design of the engine bay's panels including apertures, and a good selection of the type and location of acoustic treatments.

For a given engine bay design, the PBN SPL results can be obtained with a PBN test or by an equivalent simulation. Using simulation models it is possible to create the perfect test environment virtually and moreover to obtain acoustic results for a large number of designs upfront of any actual testing or prototype. The challenge for simulation models is however that, as the results should typically be available from 20 Hz up to 4 or 5 kHz and overall SPL results should be retrieved from a narrow band response over this large frequency range, the CAE models required can become very large and many frequencies need to be computed resulting in long solving times.

This paper will discuss on Boundary Element Method (BEM) and Finite Element Method (FEM) acoustic technologies available to predict powertrain exterior Acoustic Transfer Functions (ATFs) for a mock-up model of an engine bay. A comparison with Test results is provided to judge on the models' accuracy. Special focus is given to a comparative performance study for the different simulation approaches.

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## INTRODUCTION

In the past 10 years, not that much focus has been given to simulating powertrain exterior noise in the automotive field. Reasons for this were the fact that deterministic computational approaches (BEM, FEM), combined with the hardware available for solving such simulation models, simply were not ready yet to cover the frequency range of interest for this application (~ 4 kHz). Next to a substantial modeling effort, the limiting factor was a lack in performance of these methods. It literally would take several days to compute one case. Next to this reason from numerical acoustics perspective, the automotive industry also had perfected the métier of designing an engine bay and applying acoustic treatments to ensure a sufficient attenuation of the engine radiated noise, so the incentive to find a better optimum was not sufficiently present.

As legislation has recently put more challenging targets for PBN (70 dB(A)), a renewed interest is taken in simulation as a means to design the engine bay right first time, before an actual prototype needs to be made. Also the engine downsizing trend and the rising importance of different types of noise sources, e.g. injector and air loading systems, calls for more engineering insight in the design stage. This, together with an increase of available computational resources and ability of new simulation methods, has raised the interest to use simulations again to help making design decisions.

This paper will start with a description of the experimental setup and acoustic measurement results for an engine mock-up case. The layout of the geometry will be explained

and the effect of several setups involving the opening or closing of some apertures and application of acoustic treatments will be illustrated.

Afterwards a selection of BEM and FEM modeling and solver methods will be reviewed. Even if this section contains some equations, the idea is not to provide an in-depth theoretical description of the approaches but to mention a few key aspects to make users of such technologies understand better why these technologies are interesting for large exterior acoustic problems, as encountered in pass-by noise applications. This should also help in understanding when and how the BEM and FEM methods should be applied. For BEM, the Fast Multipole method's principles are explained. For FEM, the Perfectly Matched Layer (PML) technology and its implementation in LMS Virtual.Lab, Automatically Matched Layer (AML) are highlighted and a new promising approach FEM Adaptive Order (FEM AO) is introduced. Also for FEM, two recent solver improvements are discussed.

The paper will conclude with two numerical studies. Both simulate a selection of test cases described in the first section of the paper. A first study aims at comparing the accuracy of FEM AML and a combined approach of BEM and Fast Multipole BEM. Some conclusions can be drawn and advice will be given taking into account not only the accuracy but also the solving speed and not to forget also the modeling effort. A second comparative study involves only FEM approaches. Iterative and direct approaches are compared for accuracy and performance for the same FEM AML model. Afterwards, using a direct solving approach, the FEM AML method is compared to the new FEM AO technique recently available in LMS Virtual.Lab.

## EXPERIMENTAL SETUP AND RESULTS

A car engine bay mock-up was built using stiff plywood (see [Figure 1](#)), trying to keep the dimensions and the shape of the mock-up as close as possible to those of a real engine bay. The presence of the engine was taken into account by putting another stiff plywood structure (a kind of "engine block mockup", visible in [Figure 2](#)) inside the engine bay mock-up. The shape and the dimensions of this latter structure roughly reproduced those of an engine block (including ancillaries), leaving a relatively small air-gap (in the order of a few cm) in between its walls and the side walls of the engine bay mock-up.

Furthermore, a few apertures were made on the external walls of the engine bay mock-up, in order to simulate the main apertures normally present on the boundary of a real vehicle engine bay. A first aperture was put in the front wall (radiator, visible in [Figure 1](#)), one in the back wall (driving shaft), two small apertures in the bottom wall (to simulate the apertures normally present in the under-engine shield for ventilation purposes) and two in the side walls (apertures for wheel axles). Six flat microphones were applied approximately at the centre of the six engine block mock-up walls (see [Figure 2](#)) and a

volume velocity calibrated point source was placed outside the engine bay mock-up at two fixed positions, frontal (1500 mm far from the front face and 1700 mm high above the floor) and lateral (1700 mm far from the side face and 1700 mm high above the floor). The source in its lateral position is also visible in [Figure 1](#).

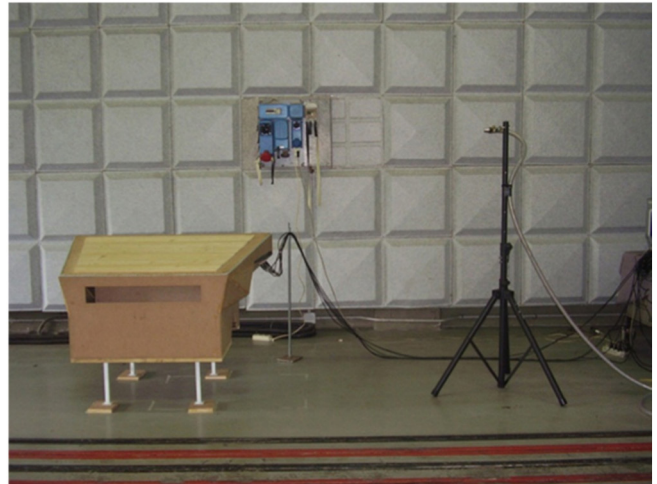


Figure 1. A front view of the engine bay mock-up during ATF tests. On the right side, the acoustic source is visible

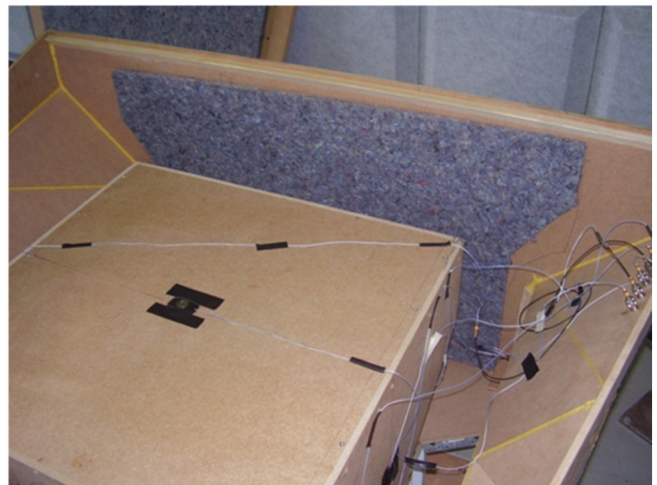


Figure 2. A view of the interior of the engine bay mock-up.

Eventually, acoustic treatments could be applied inside the engine bay mock-up on 3 different walls: under the hood, under the engine and on the back wall, i.e. the wall simulating the firewall panel (this "firewall treatment" is also visible in [Figure 2](#)). A 20 mm thick double-layer of felt was used for all the three absorbers considered. For the definition of the boundary conditions needed in the simulations, the normal incidence absorption coefficient and surface impedance of the treatment were measured in a standard Kundt Tube.

For each source position, by playing with the apertures (open or closed) and with the acoustical treatments (present or not) it was possible to measure the ATFs in several different configurations. This could be done in such a way to allow an assessment of the contribution of each aperture to the ATF.

measured at each microphone, as well as of the influence of each trim part on the same ATF. In total, 27 different configurations were measured (for each one of the 2 source positions). More details can be found in [3].

### Analysis of the Experimental Data

The analysis of the experimental data can provide in itself interesting information for what concerns the effect that the opening or closing of a certain aperture has on the ATFs for the different microphones and also for what concerns the influence that trim parts have on the same ATFs. All these aspects are analysed in this section. Results are always reported in 1/3 octaves, since this type of frequency packing is the one normally used for the measurement of exterior ATFs in the automotive industry.

### Apertures' Contributions to ATFs

Figure 3 shows for the front microphone the comparison between the ATFs measured with the source always in frontal position and for the following configurations:

- A. Conf. 1: all apertures open, no trim;
- B. Conf. 3: only side apertures open, no trim;
- C. Conf. 4: only front aperture open, no trim;
- D. Conf. 5: only rear aperture open, no trim;
- E. Conf. 6: only bottom apertures open, no trim;
- F. Conf. 2: all apertures closed no trim.

Analogous comparisons for the ATFs measured with the source in lateral position are shown in Figure 4.

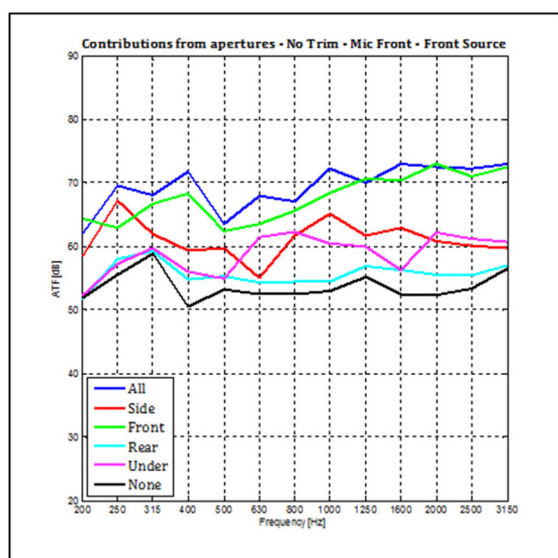


Figure 3. ATFs with all apertures open, each single aperture open, and all apertures closed (front microphone, front source)

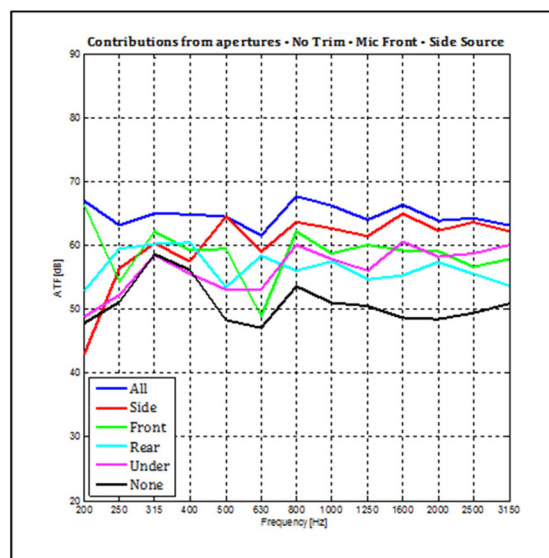


Figure 4. ATFs with all apertures open, each single aperture open, and all apertures closed (front microphone, side source)

From the data reported in Figures 3 and 4 it appears that when all apertures are open, the noise transmitted through them is - as expected- dominant w.r.t the noise transmitted through the engine bay mock-up walls. It is important to remark, though, that this is not always true when a single aperture is open, particularly in the low frequency range. Another point to be mentioned is that, always in general, the "ranking" of the contributions given by the single apertures to the microphones' ATFs is defined mainly by the relative positioning of the source w.r.t. the apertures rather than by the relative positioning of the microphones w.r.t. the apertures themselves. Interpreted in a reciprocal way, this means that for a fixed receiver external microphone, the positioning of the apertures is more important than the positioning of the sound sources inside the engine bay.

### Influence of Trim Parts on ATFs

Figures 5 and 6 show the effect (in terms of Insertion Loss, IL) of the acoustical absorbers applied on the walls of the engine bay mock-up on the measured ATFs when all apertures are open, for the top microphone (Figure 5) and for the front microphone (Figure 6). Note that the case with all apertures open but with all acoustic treatments applied is referred to later as Configuration 7 and will be used, next to Configuration 1, in the predictive simulation studies reported later in this document. The overall effect of the absorbers (red lines) is compared to the effect of each single absorber for the front source positions. From these data it appears that the effect of the applied absorbers in the mid-high frequencies is extremely high for the top microphone (up to 25-30dB) and anyhow relevant -while substantially lower- for the front microphone (in the order of 5-10dB). This difference is easily explained with

the fact that the top microphone is much closer to an absorption treatment (the hood absorber, distance ~10mm) than the front microphone. From the data in [Figures 5](#) and [6](#) it also appears that proximity effects (i.e. how close an absorber is to a receiver microphone) are as expected important but they must be interpreted taking into account not just the geometrical distance between the absorber and the microphone, but also the transfer path from the source to the receiver. For example, for the front microphone the absorber with the highest effect is actually the under-engine absorber and this might depend on the fact that, given the inclination of the front face of the engine block mock-up (see [Figure 5](#)), the reflections from the bottom surface of the engine bay mock-up play a relevant role for this microphone.

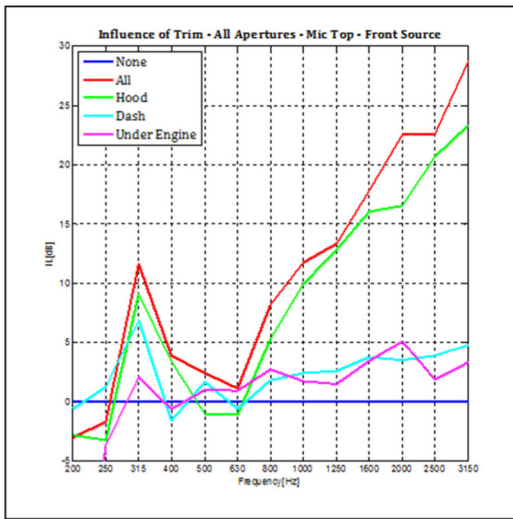


Figure 5. IL of acoustic absorbers - top microphone and front source position

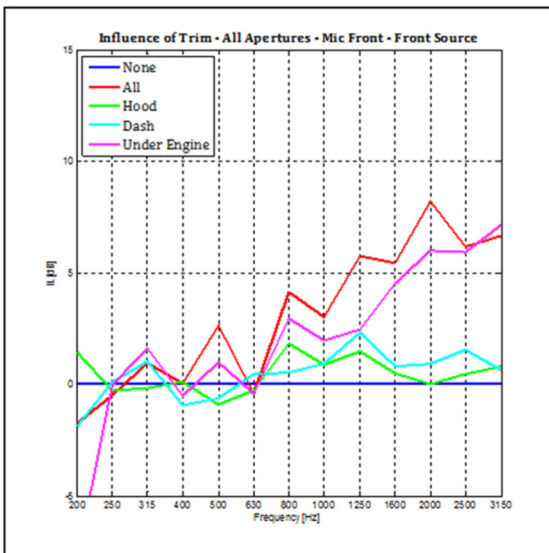


Figure 6. IL of acoustic absorbers - front microphone and front source position

## DETERMINISTIC BEM AND FEM MODELING AND SOLVER APPROACHES

Previous studies have explored a number of modeling and solver approaches for prediction of the exterior Acoustic Transfer Functions (ATFs). For the particular case of the engine mock-up case discussed in the previous section, for frequencies up to 3500 Hz, [1], [2] and [3] have investigated all together:

- Indirect BEM
- Fast Multipole BEM
- Patch Transfer Function (PTF) Method
- Infinite FEM (IFEM)
- FEM Perfectly Matched Layer (PML), Automatically Matched Layer (AML)

On a full car level [4] and [5] report on using Fast Multipole BEM for computation of exterior ATFs up to 2.2 kHz and 4 kHz respectively. The latter adds two different FEM approaches to the comparison. Together they cover:

- Fast Multipole BEM
- FEM AML
- FEM AML Adaptive Order (AO)

From the abovementioned studies, the ones underlined showed quite promising results. With the eye on highlighting the particularities and key principles to understand why these approaches proved successful, a short review or introduction for each of them will be provided in this section.

### The Uncoupled Exterior Acoustic Problem

The acoustic problem at hand is an uncoupled, pure acoustic response in a set of microphone points, given a set of sources and the description of the model's surface and (absorption) boundary conditions on this surface. This case is captured in [equations \(1\)](#), in which the first equation is the acoustic wave equation (reducing to an Helmholtz equation in case the source  $q$  at  $\vec{r}$  is zero), with  $k = \omega/c$  the acoustic wave number,  $\rho$  the fluid mass density and  $\omega = 2\pi f$  the radian frequency.  $c$  is the fluid's speed of sound. The second and third equations in [\(1\)](#) represent the velocity and impedance ( $\bar{Z}$ ) boundary conditions respectively. The fourth equation is the Sommerfeld radiation condition, which the solution for the pressure field  $p(\vec{r})$  should comply with. This to ensure no sound is reflected at infinite distance from the model.

$$\begin{cases} \Delta p(\vec{r}) + k^2 \cdot p(\vec{r}) = -\rho \alpha q(\vec{r}) \\ \frac{j}{\rho \omega} \frac{\partial p(\vec{r})}{\partial n} = \vec{v}_n(\vec{r}) & , \vec{r} \in \Gamma_v \\ p(\vec{r}) = \frac{j \bar{Z}(\vec{r})}{\rho \omega} \frac{\partial p(\vec{r})}{\partial n} & , \vec{r} \in \Gamma_z \\ \lim_{|\vec{r}| \rightarrow \infty} |\vec{r}| \cdot \left( \frac{\partial p(\vec{r})}{\partial \vec{r}} + j k p(\vec{r}) \right) = 0 \end{cases}$$



## The Boundary Element Method (BEM)

The BEM method is a well-established method for (un)coupled exterior acoustic problems. An indirect BEM formulation relates the pressure at any point to the distribution of single layer

potential  $\sigma(\vec{r}_a)$  and double layer potential  $\mu(\vec{r}_a)$  on the boundary surface of the BEM model, utilizing a Green's function  $G(\vec{r}, \vec{r}_a)$ .

$$\begin{cases} p(\vec{r}) = \int_{\Gamma_a} \left[ \mu(\vec{r}_a) \frac{\partial G(\vec{r}, \vec{r}_a)}{\partial n} - \sigma(\vec{r}_a) \partial G(\vec{r}, \vec{r}_a) \right] d\Gamma_a(\vec{r}_a), & \vec{r} \in \Omega \setminus \Gamma_a \\ \sigma(\vec{r}_a) = \frac{\partial p(\vec{r}_a^+)}{\partial n} - \frac{\partial p(\vec{r}_a^-)}{\partial n} \\ \mu(\vec{r}_a) = p(\vec{r}_a^+) - p(\vec{r}_a^-) \\ G(\vec{r}, \vec{r}_a) = \frac{e^{-jk|\vec{r}-\vec{r}_a|}}{4\pi|\vec{r}-\vec{r}_a|} \end{cases} \quad (2)$$

For points on the acoustic models' surface a similar expression as in (2) can be obtained. After surface discretization, the boundary integral formulation is first used to create an acoustic system matrix describing a set of equations between the unknown double layer (pressures) and single layer (pressure gradients). After having obtained these acoustic potentials, (2) is again used to compute the pressure in any point. This second post-processing processing step is usually not a bottleneck. More troublesome can be the first step to compute the potentials: as there are relations from every acoustic surface node to all other acoustic surface nodes, the system matrix at each frequency is fully populated. This yields a time performance that scales as  $O(n^3)$ , with  $n$  the number of degrees of freedom (DOF) in the BEM model. As we are using a surface mesh, a doubling of frequency would mean a factor 64 in computation time.

A clear advantage of the BEM methods is that only minimum modeling effort is required as only the surface needs to be discretized. BEM models will therefore always be smaller compared to equivalent standard FEM models in terms of number of DOF. This made BEM quite popular for exterior acoustics. The smaller models lead to shorter simulation times, even if the system matrix was fully populated. As this section will mention later on, the advantage of sparsely populated system matrices in FEM formulations eventually got the upper hand compared to conventional BEM methods, as the FEM model size could be drastically reduced thanks to developments of new technologies. However, new numerical approaches to solve the system of BEM equations have arisen over the past 10 years, which make also BEM again a modeling option to be considered for large exterior acoustic (uncoupled) problems.

## Fast Multipole BEM

The recently developed Fast Multipole BEM approach differs from conventional BEM in two ways [6]. The most remarkable difference is that it uses an approximate formulation to express the interactions between nodes which lie far away from each other on the acoustic model. The second difference is that the BEM problem is solved in an iterative way.

### Multipole Expansion

The core of the approach lies in a multilevel split of the full BEM model into smaller cells as illustrated in Figure 1. The obtained multi-level mesh division is often referred to as the 'octree' structure. Such structure is computed for every frequency with the smallest box length (highest level cells) about  $\lambda/4$ . Cells which are not adjacent at their level and for which the parents are not adjacent at the parent's level, can be considered far away from each other. For the influence between their nodes, the conventional Green's kernel function is replaced by expression (3), which uses Gegenbauer's addition theorem (see also Figure 7).

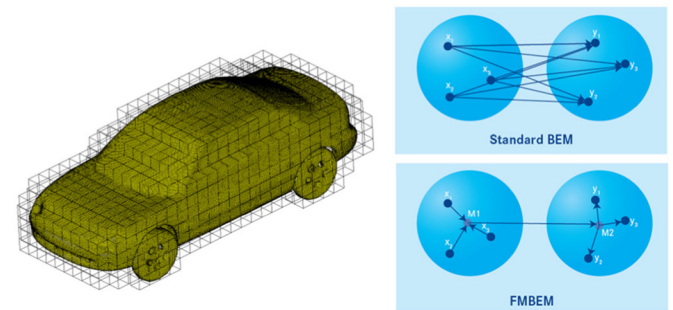


Figure 7. The Fast Multipole BEM principle

$$\begin{aligned} G(x, y) &= \frac{jk}{16\pi^2} \lim_{L \rightarrow +\infty} \int_S e^{jk(\vec{s} \cdot \vec{x} \overline{M_1})} \cdot T_{M_1, M_2}^L(\vec{s}) \cdot e^{jk(\vec{s} \cdot \vec{y} \overline{M_2})} d\vec{s} \\ T_{M_1, M_2}^L(\vec{s}) &= \sum_{0 \leq l \leq L} (2l+1) j^l h_l^{(1)}(k \cdot |\overline{M_1 M_2}|) \cdot P_l \cos(\vec{s}, \overline{M_1 M_2}) \end{aligned} \quad (3)$$

With  $S$  the unit sphere,  $h_l^{(1)}$  the first type Hankel function of order  $l$ ,  $P_l$  the Legendre polynomial of order  $l$ , where  $L$  denotes the truncated number of expansion terms.

Suppose a case with 10 nodes around pole  $M_1$ , and 10 nodes in the cell in vicinity of  $M_2$ . To obtain all 100 influences between the nodes around  $M_1$  and those around  $M_2$ , 21 operations would be needed instead of 100 with conventional BEM. This computational advantage becomes more and more outspoken, the higher the computation frequency gets, as the cell size decreases and more cells are seen to be far away from each other. Next to that, the conventional 'fully populated' BEM approach is still applied to describe influences between potentials in each single cell, but the number of nodes contained per cell also decreases with frequency.

### Iterative Solver

Fast Multipole BEM, as supported by LMS Virtual.Lab, uses an iterative solver (Krylov subspace) with a Sparse Approximate Inverse (SPAI) as preconditioner. The solver is also adapted to deal efficiently with multiple load conditions (multiple Right Hand Sides), by using Singular Value Decomposition techniques to filter out redundancy in the loads. The time performance is  $O(n \cdot (\log(n))^2)$ , which means it clearly will outperform conventional BEM  $O(n^3)$  for larger (>20k DOF) models but might be less efficient for smaller models.

### The Finite Element Method (FEM)

FEM methods are known to exhibit sparsely populated system matrices which allows efficient numerical techniques to be used for solving. When using FEM for exterior acoustic problems, the fluid around the sound scattering object needs to be explicitly modeled. As one cannot model the fluid up to infinity, the model stops at a certain distance from the scattering object and an anechoic boundary condition is applied at the outer boundary of the conventional FEM domain that should mimic the unbounded nature of the real physical problem described (satisfying Sommerfeld). Such condition can be obtained by simply applying the fluid's characteristic impedance at a faraway outer FEM boundary, as there the sound waves will indeed behave as plane waves, which means an impedance match is ensured and no reflections on the outer FEM boundary occur [7]. This approach however requires having the FEM boundary far away from the scattering object leading to huge amounts of DOF and therefore long computation times.

Two more elegant approaches are often used in FEM acoustics to obtain the anechoic boundary condition: using Infinite Wave Envelope Elements (IFEM) or using a Perfectly Matched Layer (PML) technology at the outer FEM boundary. These techniques allow for this boundary to be much closer to the scattering object, resulting in smaller models and therefore smaller computational efforts. More information on IFEM can be found in [7] and a comparison between IFEM and PML has been presented in [3]. Only the PML technology will be repeated here in this short FEM review. This subsection on FEM will moreover introduce a new approach in FEM using a frequency dependent amount of DOF. FEM Adaptive Order (FEM AO) defines the order of each element at each frequency to ensure a certain accuracy, leading to an optimal (minimal) DOF size per frequency. This clearly has a positive impact on overall computation times.

### Perfectly Matched Layer Technology

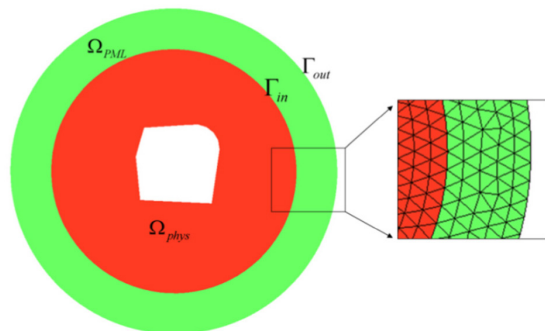


Figure 8. PML elements layer around a spherical FEM model

The PML approach requires only a finite layer to be constructed around the original FEM mesh. This finite layer can be discretized with conventional FEM elements, as illustrated in Figure 8 for a spherical original FEM mesh.

The original FEM domain is referred to as  $\Omega_{phys}$  and the PML domain as  $\Omega_{PML}$ , with  $\Gamma_{in}$  and  $\Gamma_{out}$  as PML-FEM boundary surface and outer PML surface. The methodology of PML consists in defining a transformation for the coordinates of points in the PML domain from physical real domain to the complex domain (4)

$$\forall x \in \Omega_{PML} : x \rightarrow \hat{x} = x + \frac{f(x)\vec{n}(x)}{jk} \quad (4)$$

In (4),  $x$  and  $\hat{x}$  represent the full real or complex coordinates.  $f(x)$  is an absorption function varying across the PML domain from 0 at  $\Gamma_{in}$  to a finite value at  $\Gamma_{out}$ . In case the absorption has a zero slope at  $\Gamma_{in}$  the artificial layer is said to be “perfectly matched”, since no discrepancy is introduced at  $\Gamma_{in}$ . As a result, no reflections will occur at  $\Gamma_{in}$ . For a wave traveling outwards, the absorption will be gradually built up as the wave propagates through the PML domain and travels towards  $\Gamma_{out}$ . The PML medium is however not isotropic, as the absorption is applied only along a vector  $\vec{n}(x)$ . This vector  $\vec{n}(x)$  can easily be defined for cases in which basic canonical shapes are used for the original FEM model like spheres or boxes. However the locally-conformal formulation [8] allows for any convex surface  $\Gamma_{in}$ .  $G$  to be used as basis for constructing the PML layer (by means of meshing a CAD volume or extruding the FEM element faces of  $\Gamma_{in}$ ). Figure 9 illustrates the PML model with convex  $\Gamma_{in}$ .

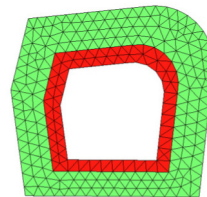


Figure 9. PML configuration for convex  $\Gamma_{in}$

The same scaling as in Figure 2 has been used in order to underline that with the locally-conformal PML approach, the size of the original FEM domain can be drastically reduced. This will clearly have an effect on the computation times and memory requirements.

Beriot and Tournour [8] investigated the accuracy and stability of the locally-conformal PML method for different approaches of finding the unit vectors  $\vec{n}(x)$  in the PML domain. It is of utmost importance that these vectors are perpendicular to  $\Gamma_{in}$  in the vicinity of  $\Gamma_{in}$ . In case the absorption vectors would contain an in-plane component with respect to  $\Gamma_{in}$  and near to  $\Gamma_{in}$ , waves which exhibit propagation in the opposite in-plane direction will be amplified in the PML layer.