MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Electric motor encapsulation design for improved NVH: a CAE-based approach

Federico Di Marco, Roberto D'Amico, Francesca Ronzio
Autonuem Management AG
Schlosstalstrasse 43, Winterthur 8406, Switzerland

ABSTRACT

The increasing number of battery electric vehicles (BEVs) challenges NVH engineers with many new problems, such as tonal noise, whistling, whining noise and many others, which affect the development of the NVH package. Simulation methodologies and CAE workflows are being enhanced to contribute to EVs development and improvements.

In this article, a numerical activity aimed at assessing the potential of e-motor encapsulation with respect to exterior and interior noise reduction is presented. The core of this activity is to provide an easy and reliable CAE workflow to enable NVH engineers to design e-motor treatment in the early design stage, when full characterization of e-motor emission spectra or electromagnetic excitation sources are not yet even available.

To achieve that, the model of a simplified e-motor is analysed first with acoustic simulation in free field under a set-up resembling an engine test-bench. Then, such a model is inserted in an engine bay mock-up. The performances of the different encapsulation materials and the existing trade-off between insulation and absorption are assessed.

Keywords: battery electric vehicles, engine encapsulation, acoustic treatment, electric motor, NVH

I-INCE Classification of Subject Number: 30

Click here to check teh I-INCE Classification http://i-ince.org/files/data/classification.pdf

1. INTRODUCTION

The automotive industry is going through disruptive times, and the core of such a disruption is the change in the propulsion system from the established Internal Combustion Engine (ICE) to an electric motor. This change impacts almost all the engineering aspects of the vehicle, starting from the structure of its Body-in-White to the overall vehicle architecture, without excluding NVH: the broadband roaring of a combustion engine will be replaced by a high-frequency tonal whistling, with evident impact on acoustic comfort, perception and performance.

In recent years, ICEs have been more and more equipped with engine encapsulations [3, 4]. An engine encapsulation is a passive treatment, whose primary functions are heat retention and noise reduction driven by ever tightening regulations. Designing an engine encapsulation is not an easy task. It requires taking into account several constraints together with ensuring a desired acoustic and thermal performance.

Additionally, moving from an ICE to an e-motor encapsulation brings new and diverse challenges to engineers, who should make wise use of the tools at hand to address better NVH. For example, e-motors present issues at higher frequencies with respect to ICEs. Additionally, they have different size and shape.

As discussed in [1,2], in order to assess the performance of an engine encapsulation an engineer must account for two key aspects. Firstly, the design of the encapsulation and secondly the optimal Bill of Materials (BOM) for that specific design. However, while in [1,2] such a process is presented for ICEs, in this paper the discussion is moved to e-motors. In particular, this work focuses on the design decision making process when it comes to the aforementioned choices. In such a context and given the need for a quicker and quicker time-to-market, relying on CAE and virtual processes is today a necessity of engineering departments. The old-fashioned design-test-optimize loop is extremely restrictive, demanding and costly. In this direction, the tools presented in [1,2] and in this paper, provide engineers with a reliable, robust and yet efficient toolbox, that allows tackling design questions effectively and timely.

Acoustic simulation can support decisions at two principal levels [1]. The first level involves the material only and it enables the choice of the pile-up to ensure the desired performance-to-weight ratio. This process can be supported by the so-called Transfer Matrix Method (TMM) [6], and allows the prediction of the absorption and insulation performance of at flat, 2D sample. The second level includes the geometrical complexity of the treatment and its boundary conditions, and it requires the use of Finite Elements Method (FEM). Although building up a FEM model requires a higher level of effort with respect to TMM, it also delivers a higher accuracy and the possibility to include high-fidelity details into the problem at hand [1].

Both levels are presented in this paper with reference to novel BOMs for an e-motor encapsulation. After an initial introduction about the key differences between encapsulations for ICEs and e-motors, the acoustic performance of different BOMs is shown at material level first with TMM. After this, the performance of the aforementioned BOMs is assessed at e-motor level with FEM.

2. E-MOTOR ENCAPSULATION DESIGN

In terms of design, e-motor encapsulations are mainly engine-mounted. This means that the treatment is in the near vicinity of the engine surface, and in most of the cases even in contact with this surface. The key design principle of encapsulation still holds true for e-motors: the higher is the coverage of the encapsulation, the higher its acoustic performance, being the coverage the ratio between the area of the motor covered by the treatment to the total area of the motor. Generally, 80% coverage guarantees good acoustic improvements for ICEs, and such a rule-of-thumb is confirmed for e-motors.

The main geometrical differences between the two propulsion systems are the shape and the size. E-motors are characterized by a mainly cylindrical shape with axis that commonly is parallel to the one of the wheels. ICEs have a dominant vertical extension, which culminates with the gearbox. Additionally, E-motors are smaller than ICEs and have less ancillaries and pipes. This strongly impacts the geometry of the encapsulating parts. In the case of ICEs, the treatment usually consists of smaller and often flat parts – with the exception of the oil sump and gear box cover. In the case of e-motors, it is more common to have curved parts, that in some cases envelope the whole motor. Such differences strongly impact the design decisions and also the process to be put in place to manufacture the components.

Figure 1. ICE [1] vs e-motor geometry

When it comes to the choice of the BOM, some differentiation has to be done between ICEs and e-motors. From a perspective of the technical requirements the BOM must satisfy, the main differences between ICEs and e-motors are related to resistance to vibration and temperature levels. In fact, ICEs present higher operational vibrations, which require higher durability of the material. Additionally, ICEs expose the materials to higher temperatures, while e-motors have commonly operational temperatures reaching max 80-90°C.

A key point of differentiation is the spectral acoustic content of the source. The relevant frequency range for ICEs generally reaches 2.5-3kHz. In the case of e-motors such a range moves up to about 5kHz (even higher, if one includes the contribution from power electronics). Additionally, in the case of ICEs the combustion and structural noise dominate the noise radiation. Of course intake, ancillaries etc. also contribute relevantly to the overall acoustic radiation. For e-motors things are totally different. Structural, electro-magnetic and aerodynamic content are contributing. The way the engine is controlled, i.e. with PWM, could lead to switching noise. Structural case modes excited by the rotor electromagnetic forces also have an impact on the overall noise emission. Finally, the gearbox unit can show some whining. The key difference between the two noise spectra lies in the fact that high-frequency, tonal noise characterizes e-motors, rather than a broadband content. As a consequence, the acoustic treatment must account for such a difference in noise emission.

3. PERFORMANCE ASSESSMENT AT MATERIAL LEVEL

Generally speaking, the BOMs for encapsulation can be classified either as single layer or as dual layer constructions. In the latter case, a foil can be placed between the two layers with the function of regulating the overall Air Flow Resistivity (AFR) of the construction. Usually a single layer material can be a closed cell PU foam, with a relatively high density, because of ease of positioning of the component on the engine, or an acoustic absorber, like open foam or felt. In the case of a dual layer material, distinction must be made between the constructions with no or open foil, and those with impervious foil. The former are commonly absorber materials. The layer facing the engine bay is called carrier and has the functions of increasing the Transmission Loss (TL) of the pile-up and provide structural support to the part. The other layer shows higher absorption and is called decoupler or absorber. Higher IL can be achieved if the foil is impervious, as it is shown later. (comment CB: even though what is written here above is correct, I think it could be misleading to leave it in the paper in this section. It appears also a bit out of context, in my view).

When it comes to the choice of the materials to achieve the desired acoustic target, one must consider that often the performance of a part is not just reflected by its absorption and TL characteristics, but it is rather obtained from a balance of these two quantities that takes into account the “acoustic environment” in which the part is installed.. This can be quickly seen by recalling the following simple mathematical relation that quantifies the IL (capsule index) of a generic acoustic enclosure [5]:

$$IL_{capsule\ ind.} = 10\log_{10}\left\{\frac{\frac{S_w}{S_A}(\alpha_d + \tau_d) + 1}{\frac{S_w}{S_A}\tau_d + 1}\right\}\ [\mathrm{dB}] \qquad (1)$$

whose symbols are explained in Figure 2. Equation (1) is very simple, yet it takes into account all macro-variables driving the acoustic performance of an encapsulation, namely coverage ratio, openings and acoustic properties of the materials. Equation (1) also reveals that using either purely absorbing or insulating materials alone is not enough to reach the best performance. While high TL is necessary to retain the noise, high absorption allows dissipating it and reducing the leaks through the openings. Thus, both acoustic characteristics are necessary and must be well-balanced.

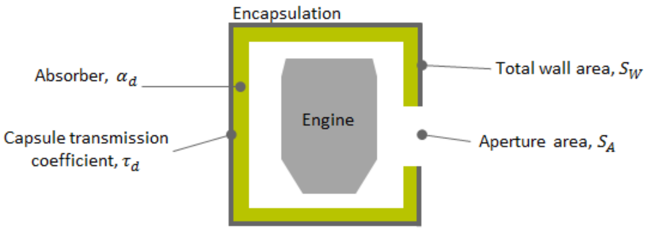

Figure 2. Simple model of engine encapsulation.

Equation (1) can be very handy for an early assessment of the capsule performance. Nevertheless, more accurate and specific tools are necessary to account for the full complexity of the problem, which includes several additional aspects. For instance, the part geometry and thickness distribution play an important role, as well as its position with respect to the engine. Furthermore, when assessing the vehicle level performance, the acoustic engine bay package must be considered.

In order to calculate the acoustic characteristics of the material in Equation 1, the TMM approach can be easily used [6]. Within the TMM, the material is assumed to be of infinite extent. No edge, boundary or fixation effects are taken into account in the simulation, although a software like VisualSisab [9] allows including the thickness distribution of the part. However, in general the TMM is suitable for quick material assessment, as it allows predicting the acoustic performance of a BOM in a handful of seconds.

Let us start by analysing the performance of different BOMs and consider those reported in Table 1:

- BOM 1 is a classic acoustic mass-spring system. A felt material on the decoupler side provides a rather soft spring to ensure good acoustic performance. BOM 1 mixes well a high TL and a relatively good absorption (from the decoupler side, as proposed in equation 1).
- BOM 2 consists of an absorber with an impervious foil on top.
- BOM 3 adds to BOM 2 a compressed felt top layer. Also in this case the previous equation is followed, but with a lower weight.

- BOM 4 is a purely absorptive solution. The compressed felt on top allows anyway an acceptable level of TL.
- BOM 5 is similar to BOM 3, but the felt material ensures a much softer spring. The absorption of the decoupler is lower than the open slab foam of BOM 3, though.
- BOM 6 is a classic closed, heavy foam. No or little absorption limits the acoustic performance of such a solution to the mass effect.

BOM	**BOM 1**	**BOM 2**	**BOM 3**	**BOM 4**	**BOM 5**	**BOM 6**
Layer 1	mass layer	impervious film	felt layer	felt layer	felt layer	closed foam
	2000gsm, 2mm	100um	1000gsm, 5mm	1000gsm, 5mm	1100gsm. 5mm	3910gsm, 14mm
Layer 2	felt layer	open foam	impervious film	open foam	impervious film	
	750gsm, 12mm	330gsm, 14mm	100um	330gsm, 9mm	100um	
Layer 3			open foam		felt layer	
			330gsm, 9mm		600gsm, 9mm	
Total gsm	2750	330	1330	1330	1700	3910

Table 1. Selected BOMs for encapsulation analysis. Layer 1 is towards the engine bay.

Following Equation 1, it is interesting to see how the IL capsule index (averaged from 1 to 3.5kHz) quickly grows with the coverage, Figure 3 (left). One can easily note that the rate of growth significantly increases for coverages above 80%. Figure 3 (right) focuses on 95% coverage of the engine, and compares the IL capsule index to the total grammage of the BOMs. From the chart, it is rather clear that mass is not all, see performance of BOM 6. A combination of high TL and absorption can lead to good performance, like in the case of BOM 1. However, by replacing the mass layer with a compressed felt, like in the case of BOM 3 and 5, it is possible to achieve good acoustic performance at a lower weight. It is also very interesting to compare BOM 3 and 4. The difference in performance is given by the presence of the impervious foil, which highly improves the TL of the construction.

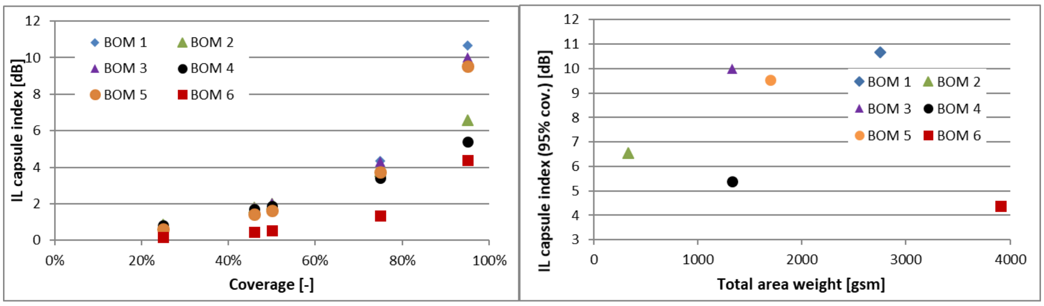

Figure 3. IL capsule index vs coverage for BOMs in Table 1 (left). IL capsule index vs total gsm for BOMs in Table 1 at 95% coverage (right).

The IL capsule index formula refers to an acoustic encapsulation, and it is extremely useful and handy for quick calculations. However, it does not account for the contact between the part and the engine surface. While for ICEs encapsulation is commonly not in direct contact with the engine surface, for e-motors this is often the case. And when the treatment and the source are in direct contact, vibration is transmitted also directly. This has consequences on the performance of the component. Figure 4 compares the airborne IL of the aforementioned BOMs when mounted on a steel plate, 0.75mm (Autoneum's Isokell measurement system [10]). The key difference with the data presented in Figure 3, is the exchange in ranking of BOM 5 and 3. As reported in Table 1, these two BOMs are conceptually similar, but BOM 5 has a dynamically softer decoupler, which leads to a better IL performance.

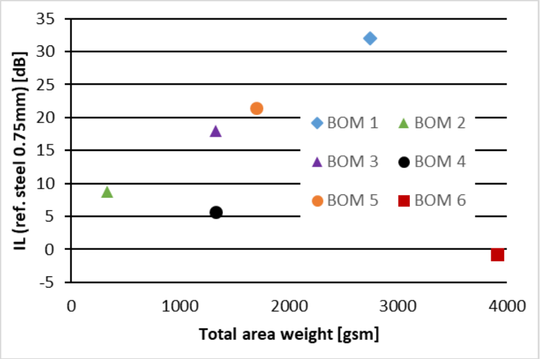

Figure 4. Average IL (w.r.t. to 0.75mm thick steel plate) vs total gsm for BOMs in Table 1.

4. PERFORMANCE ASSESSMENT AT ENCAPSULATION LEVEL

When moving from material assessment to part and vehicle assessment, boundary conditions and geometrical details must be included into the analysis. For this reason, using TMM is limiting, and FEM is currently the state-of-the-art solution, which is also commercially available.

Before going into the details of the proposed application, it is worth discussing the boundary conditions for the model. In reality, the engine vibration is extremely complex. This is true both for ICEs and e-motors, and impacts the acoustic modelling and performance prediction. However, because the goal of the design process is to identify the most performing BOM and configuration, rather than comparing absolute SPL or radiated power, it is natural to investigate deltas, i.e. differences between treated and untreated noise source. On top of this, it could be fairly assumed that the presence of the treatment does not modify the vibration of the source, hence a uniform velocity boundary condition can be applied over the whole engine surface, as already proposed and discussed in [1], as long as the delta is used as an output. In Figure 5, it is proposed a comparison between measured and simulated delta SPL (enveolope of 5 mics for a running e-motor treated with a prototyped capsule. In the simulations, a unit surface normal velocity boundary condition is applied. Although data are anonymized for confidentiality reasons, the plots share the same max and min delta SPLs, and they are scaled according to the frequency range. By comparing the two it is possible to see a good match in terms of prediction, despite the rough approximation of the velocity profile. The shifts in frequency of the peaks are mainly due to the material models, which are not fully representative of the prototype mounted on the e-motor. However, it is fair to conclude that applying a uniform unit velocity is an efficient and quick way to address design matters.

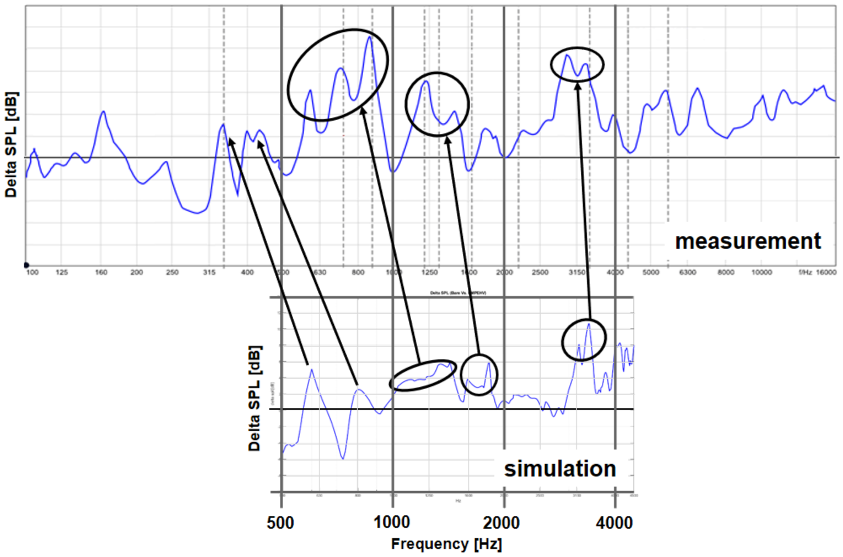

Figure 5. Comparison between measured and simulation SPL.

The engine under investigation is a simplified version of an existing one. Figure 6 shows its features. The orange area is the actual motor, the cyan is the gearbox and the green is the power electronics unit. On the right hand side of the picture, the violet area represents the encapsulation, which covers about 50% of the overall area of the engine, with constant material thickness of 14mm. The BOMs presented in Table 1 are used here as encapsulation material.

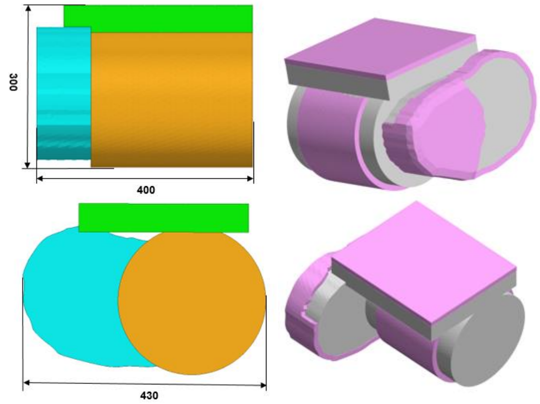

Figure 6. Simplified geometry of e-motor, its dimension and simplified capsule.

The software used for the simulations is Actran, which allows modelling FE problems in unbounded fields, and the inclusion of full Biot formulation for porous materials. Results are post processed in terms of radiated power. Although SPL is the usually measured quantity, assessing the radiated power provides a more complete information. Additionally, compared to experimental techniques, simulation allows the assessment of the radiated power over large surfaces, like hemispheres, besides allowing the free visualization of vector and scalar field with extreme ease.

The choice of using full Biot elements is justified by the necessity of taking into account all wave propagation through the material layers. This choice becomes even more relevant when dealing with a complete engine bay. Additionally, the encapsulation part is at 0.5mm distance from the surface of the motor, hence there is no direct structural transmission between the source and the capsule. For this reason, this problem is a pure acoustic one.

Running the acoustic simulation of this engine requires a pre-processing time of about 8 hours for the preparation of the simulation model, a running time which can vary between 8 hours and 14 hours, depending on the model size, and a post-processing time of 2 hours to analyse the results.

Figure 7 shows the delta radiated power as a function of the frequency for all BOMs (right-hand side picture excludes BOM6 to better show the difference between the other BOMs). The performances of the different BOMs are not significantly different from each other. This is mainly due to the 50% coverage, see Figure 1. Overall, what has been discussed in the previous section is confirmed here. BOM 1 shows the best performance at low frequencies, while BOMs 3 and 5 are more performant at higher frequencies. BOM 2 and 4 show a lower performance, although the worst in class is BOM 6. This is mainly due to the high stiffness of this foam and the absence of absorption towards the engine. For this reason, BOM 6 is even amplifying the engine radiation around the internal resonance of the material, at 1-1.5kHz.

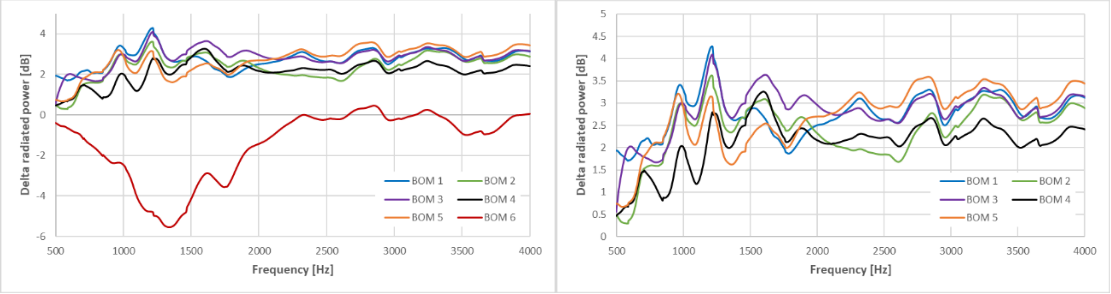

Figure 7. Delta radiated power from the e-motor with different encapsulating materials.

At this point it is worth comparing these results with the outcome of the analysis described in previous section. This is done in Figure 8, where the IL calculated with Equation 1 is compared with the outcome of the simulations in terms of equivalent radiated power. Results are very comparable both in terms of performance range and ranking. Main difference is the performance of BOM 6. This bias might be due to the fact that there is little absorption and a predominant vibration transmission which is not accounted for in Equation 1. This might lead to biased results.

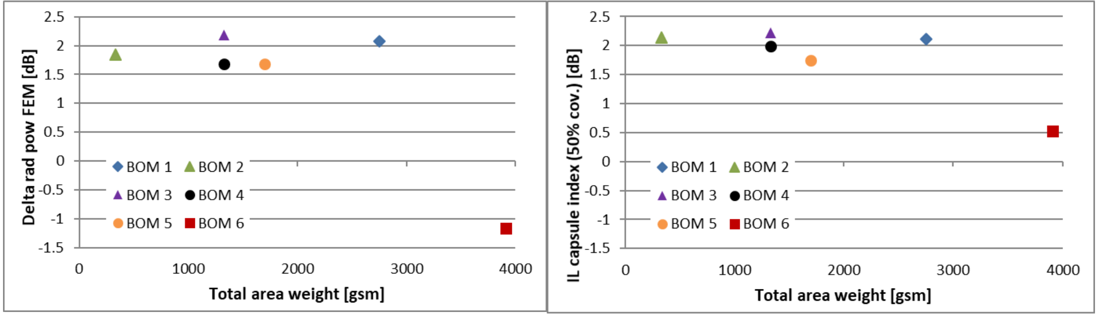

Figure 8. Average Insertion Loss assessed with Equation 1 (right) and with FEM (left) for the same BOMs and 50% coverage.

Results shown so far confirm the relevance of having an absorbing layer towards the engine. They also show that, for a low coverage of about 50%, introducing an impervious film (and thus increasing the TL) does not necessarily provide a significant increase in performance. On the contrary, when increasing the coverage above 80%, introducing either an impervious film or layer in combination with the absorber leads to non-negligible benefits, see Figure 3.

5. PERFORMANCE ASSESSMENT AT VEHICLE MOCK-UP LEVEL

This last section describes the prediction of the performance at vehicle level, where the vehicle is represented by an engine bay mock-up [7] [8]. This mock-up has been extensively used and validated in the past, and here it is enriched with the electric motor described in the previous section.

The engine bay is equipped with a classical package, namely a hood liner, an outer dash and an under engine shield. These components are modelled with porous elements, implementing full Biot formulation. The walls of the mock-up are fully reflective. Apertures are also present, as they constitute a key acoustic path towards the exterior field. All this is shown in Figure 9.

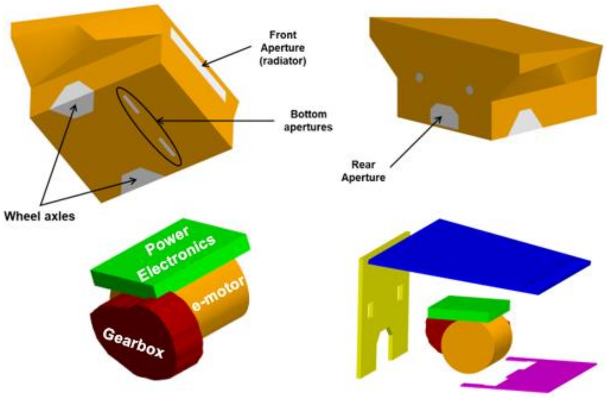

Figure 9. Simplified geometry of engine bay, e-motor and engine bay acoustic treatments

Field points are placed all around the engine bay mock-up following a hemisphere. Radiated power is calculated over this surface.

Once again simulations are carried out by assigning the BOMs in Table 1 for the encapsulation. Figure 10 shows the delta radiated power, in third octave bands, versus the frequency for all BOMs (right-hand side picture excludes BOM6 to better show the difference between the other BOMs).

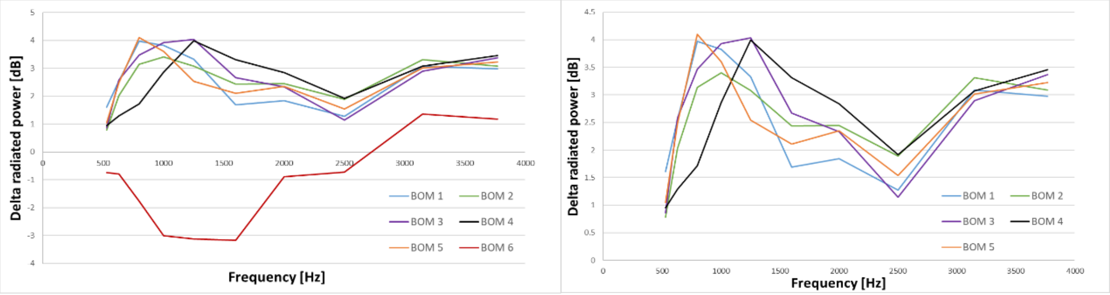

Figure 10. Delta radiated power, in third octave band, from the e-motor with different encapsulating materials.

At this point it is worth comparing these results with the outcome of the analyses on the e-motor radiating in free field (described in previous section). This is done in Figure 11, where the outcome of the simulations in free field conditions is compared with the outcome of the simulations with the engine bay.

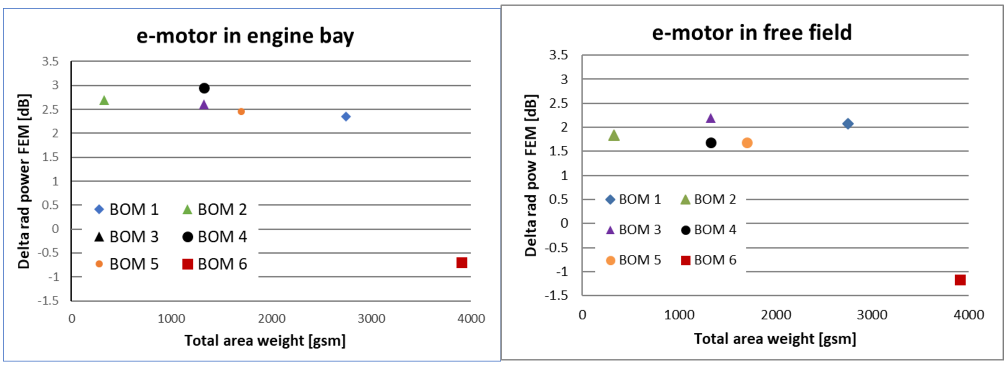

Figure 11. Average Insertion Loss with e-motor radiating in free field and with engine motor positioned inside engine bay for the same BOMs and coverage.

As it simple to observe all the BOMs have an improvement in the engine bay simulation but this melioration is not equal for all them and this changes the final ranking of BOMs. Indeed, in presence of the engine bay the BOM which performs the best is no longer BOM 3 but it is BOM 4. It has to be highlighted that BOM 4 is BOM 3 without impervious film between the two layers, this means that BOM 4 has a higher absorption than BOM 3 but a lower TL. Therefore, it is possible to conclude that, in “engine bay conditions”, when the area coverage of the capsule is below 80% the parameter which mainly drives the performance of the capsule is the absorption. The explanation for this behaviour is simple: when the coverage is low, large part of the noise radiated does not go through the capsule, so a high or low TL does not have so much impact on the performance of the capsule, but all the radiated noise hits the engine compartments walls and it is reflected back giving the chance to the capsule to absorb part of the noise before that it has the possibility to leave the engine bay through the apertures.

On the other hand, when the area coverage is above the threshold of 80%, the situation drastically changes. Once passed the 80% large part of the noise has to pass through the capsule and this means that the parameter which mostly drives the encapsulation performance is the TL. This has been confirmed by new simulations in engine bay in which the area coverage of the capsule has been increased from 50% to 90%. Figure 12 shows that in this conditions BOM 3 (higher TL, lower ABS) has a performance clearly superior to that of BOM 2 (lower TL, higher ABS).

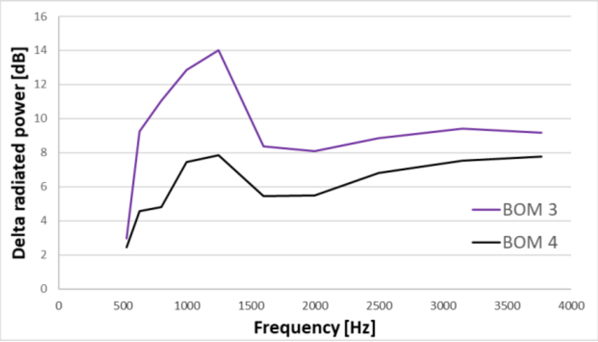

Figure 12. Delta radiated power, in third octave band, from the e-motor 90% covered by BOM 3 and BOM 4.

6. CONCLUSIONS

Electrification is bringing a significant change in the automotive world, such change is determined by the change of the vehicle powertrain. This strongly impacts also vehicle NVH, not only in terms of noise emissions, but also in terms of countermeasures to be adopted to achieve a satisfactory acoustic comfort in the passenger compartment interior.

During NVH development the definition of countermeasures can go through different levels of analysis:

- Analyses at material level allow ranking different treatments in terms of basic acoustic measurables such as absorption and insulation.
- Analyses at component level allow taking into account the design of the parts (primarily the coverage and the thickness distribution).
- Eventually, analyses at vehicle level allow taking into account the acoustic environment in which the part is installed (the level of reverberation of such environment, the presence of holes).

Examples reported in this paper have shown that at all these levels CAE tools can concretely support the development process in making informed decisions, optimize the package in terms of performance/weight and reduce to a minimum (or possibly eliminate) last minute trouble-shooting.

7. REFERENCES

1. R. D’Amico, R. Stelzer, J. Grebert, P. Chandler, G. Fossaert, *“On the role of simulation to account for design complexity of engine encapsulation”*, Automotive Acoustic Conference 2017, Zürich (2017)
2. R. D’Amico, R. Stelzer, A. Bihhadi, T. Courtois, *“Engine encapsulation: impact on vehicle NVH and CAE challenges”,* International Conference on Noise and Vibration Engineering, ISMA2016, Leuven (2016)
3. T. Bürgin, C. Bertolini, D. Caprioli, C. Müller, “*Engine encapsulation for CO2 and noise reduction, ATZ worldwide, 116(3), 16-21 (2014)”.*
4. C. Bertolini, D. Caprioli, J. Horak, T. Bürgin, D. Petley, W. Jansen, B. Wicksteed, *“Acoustic benchmark of different CO2 encapsulation strategies: application examples and methods for the design of powertrain encapsulation”*, Automotive Acoustic Con-ference, Zürich (2013).
5. F. Fahy, *“Foundations of Engineering Acoustics”*, Elsevier, 2nd edition (2005).
6. J.-F. Allard, N. Atalla, *“Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials”*, John Wiley & Sons, 2nd edition (2009).
7. G. Miccoli, G. Parise, N. Totaro, “*Simulation of the effect of the absorbing treatments in the engine compartment on the acoustic transfer functions from the powertrain surface to exterior receivers”*, Automotive Acoustic Con-ference, Zürich (2011).
8. A.Bihhadi, C. Bertolini, G. Miccoli, “*Simulation of exterior powertrain acoustic transfer functions using IFEM and other deterministic simulation methods”*, Automotive Acoustic Con-ference, Zürich (2013).
9. P. Bertolo, “Visual SISAB: a visual tool for a quick and accurate assessment of the acoustic properties of car parts”, Proceedings of Rieter Automotive Conference 2007,
10. A. Chappuis, “Small Size Devices for Accurate Acoustical Measurements of Materials and Parts Used in Automobiles”, SAE Technical paper 931266, 1993