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Addressing acoustic behavior of hybrid and electric vehicles

Using the source-transfer-receiver methodology to avoid noise, vibration and harshness issues

Executive summary

Although electric vehicles are significantly quieter than vehicles with an internal combustion engine (ICE), they bring their own noise, vibration and harshness (NVH) challenges. Not only is the high-frequency tonal noise often perceived as annoying; also, traditional noise sources like wind or tire noise are no longer masked by the dominant ICE noise. In addition, the absence of exterior sound at low speeds is a concern for automotive original equipment manufacturers (OEMs) and regulators in terms of pedestrian safety, particularly for those with visual impairments. This paper describes how to address complex NVH problems by breaking each issue into source-transfer-receiver components. Using this methodology helps to identify the root causes of late design issues and offers the possibility to implement design changes later on.

Introduction

The demands for greener transport in the last decade have resulted in a large variety of new powertrain and vehicle designs. Powertrain electrification is one of the key enablers for the future automobile industry to reach lower CO_2 emission targets. This involves the use of new concepts whose inherent characteristics, performance, and constraints vary significantly from traditional internal combustion engine vehicles. Likewise, the same holds for the NVH behavior. Although electric vehicles are significantly quieter than equivalent ICE-powered versions, their interior noise is marked by high-frequency tonal noise components with multiple coupled and independent base frequencies that are often perceived as annoying. The inclusion of new power electronics, and more particularly the pulse width modulation (PWM) control, produces specific sound modulation patterns. Simultaneously, the traditional broadband noise sources like wind or tire noise, as well as other disturbing noise radiating from various other components like the oil pump, HVAC, alternator or transmission systems, are no longer masked by the previously dominant internal combustion engine noise.

This lack of masking results in complex sound signatures with potential negative impact on user perception of vehicle performance and quality. Moreover, in order to maximize driving range and performance while moderating battery costs, achieving acceptable NVH performance becomes an even bigger challenge with lightweight vehicle body design stretched to its limits.

Besides the interior noise, the influence of electrification on exterior noise is of significant concern also. On the one hand, electrification is observed as a means to reach a substantial reduction in environmental noise pollution; on the other hand, there is the risk that quiet vehicles will go unnoticed by pedestrians and other vulnerable road users (visually impaired persons and others) as well as ICE vehicles, creating a potentially hazardous situation in urban areas. The solution to this problem is to alert the other road users to the vehicle approach with broadcast warning sounds that can alert pedestrians with minimal community annoyance. The increasing complexity of the NVH problem is summarized in figure 1.

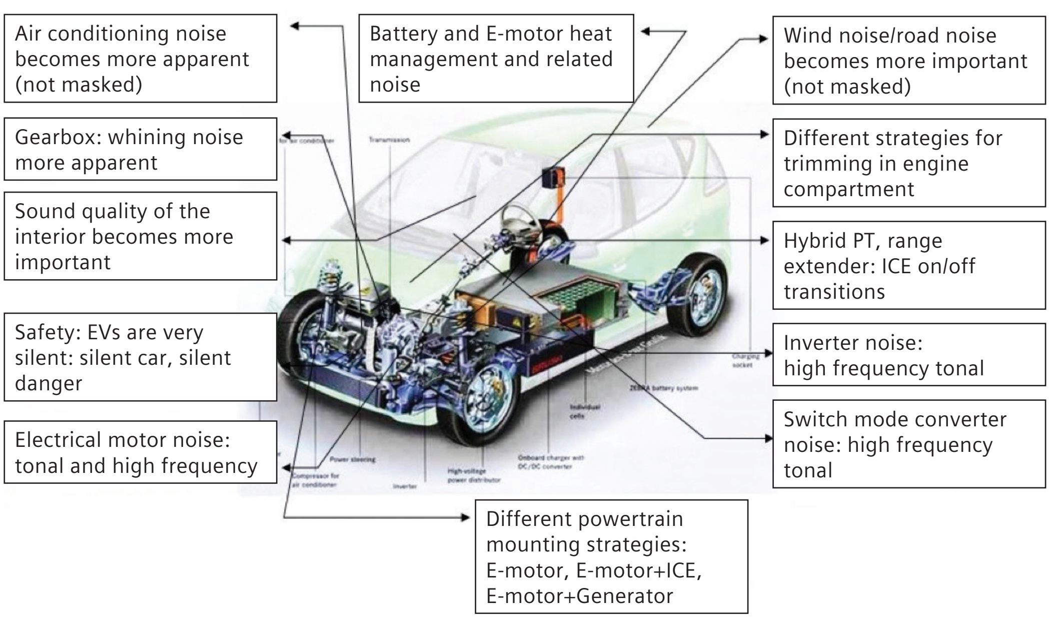

Figure 1: NVH challenges of hybrid and electric vehicles.

Source-transfer-receiver methodology

One of the best approaches to address the complex NVH problems described above is to break each issue into its source-transfer-receiver components. Using this methodology provides three individual design aspects where any improvements made will result in the global response.

Source

Since the internal combustion engine is deemed as the major noise source in conventional vehicles, the noise levels related to an electric vehicle are significantly lower due to the missing engine. Therefore, the noise signature in electric vehicles is not only different than the one in conventional vehicles, but generally a lot more complex. Some such striking differences can be seen in figure 2.

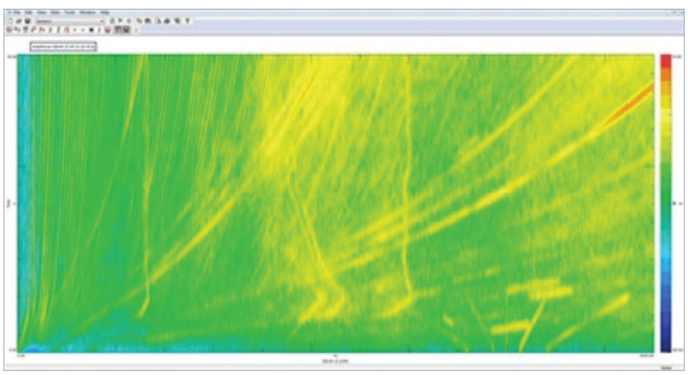

Figure 2: Noise signature of hybrid electric vehicle (HEV).

First, we must acknowledge that hybrid and electric vehicles feature new noise source components, such as electric motor(s), power electronics, and others. These components possess different operational and noise characteristics than those encountered in conventional engines. Also new are the modulation phenomena caused by the variable speed drive (VSD) inverter, which uses a pulse width modulation technique for controlling the rotational speed of the electric motor. The VSD modulations expose a typical harmonic structure in the noise footprint, composed by one or multiple central carrier frequencies surrounded by pairs of engine speed-dependent side bands. In addition, there are high-frequency tonal components resulting from the magnetic fields during electric driving and regenerative braking. Such noise characteristics are perceived as unpleasant and result in whining or whistling noise in the interior of the vehicle. Due to the lack of masking effect coming from the ICE, the noise levels of several other source components such as the transmissions, HVAC, fans, oil pump, and tires become significantly audible. Altogether, these noise sources can be extremely disturbing and must be included in the design analysis stage.

What is equally challenging in the case of hybrid and electric vehicles is the transient phenomenon, such as the extremely fast, almost abrupt changes of the engine speed during fullload acceleration. In addition, large amplitude variations of the electric whine noise occur during vehicle acceleration and braking – making the signature analysis even more difficult. Most common examples are the frequent start/stop operations of the combustion engine in hybrid vehicles, and the switching noise of the power cooling unit.

Taking all these elements into account, it is clear that the noise signature of hybrid electric vehicles features a higher level of complexity that cannot be handled by the techniques developed in view of ICE, for which the noise is dominated by a limited set of low-order harmonic components related to a single rotations per minute (RPM). Therefore, the newly adopted methods must deal with complex harmonic structures consisting of multiple groups of order and modulation components with coupled or independent base frequency (multiple rotation speeds, secondary components), with closely-spaced and crossing orders, and with fast varying order profiles, particularly in transient operating conditions.

Transfer

The radically changed noise signatures of electric powertrains also require different techniques and models in order to describe the noise transfer from the different noise sources to the receiver points – for example, the driver's ears. The main problem is related to a much higher frequency range of the sources, thereby implying reconsideration of the formulations that are used to describe and model the propagation.

The key experimental technology to be reconsidered in the view of these HEV challenges is transfer path analysis (TPA). TPA is an experimental technique that allows the identification of the structure-borne and air-borne transfer pathways from sources to receiver, based on operational data and frequency response function (FRF) measurements. This method has existed since the 1980s and has focused on the lower-frequency order components only, which dominate in traditional ICE vehicles. Hybrid electric vehicles, however, pose new challenges. First, TPA methods must be capable of dealing with the higher frequencies that play a prominent role in HEVs. The traditional TPA approach appears to break down at frequencies above a certain threshold, most likely because of the large variability of the FRF phase behavior. This requires the development of energetic, power-based TPA formulations. Second, the complex source signatures of HEV face the pseudo-domain TPA formulations. Such a time-domain approach allows auralization and sound quality analysis of the source-path contributions to the target responses.

An example (1): EV lightweight NVH design

The fact that electric vehicles (EVs) are in general quieter than their ICE counterparts provides automotive manufacturers opportunities to reduce the mass of acoustic treatments and structural reinforcements on the vehicle body. A study to map out what the primary considerations might be at a concept design stage was conducted for the future steel vehicle (FSV), a lightweight steel body with an electric motor developed by World Auto Steel [1].

Measurements were conducted on two small vehicles that share the same body: one was equipped with an ICE and the other with an electric motor (e-motor). The outcome was used as a starting point to identify assets and pitfalls of electric motor noise and to draw a set of NVH targets for the FSV. Compared to the ICE version, the e-motor vehicle showed significantly lower sound pressure levels at the driver's ear location, except for an isolated high-frequency peak heard at high speeds. This peak is situated around 3,500 Hz when the vehicle drives at top speed. Figure 3 shows the logarithmic frequency spectrum during run-up. From multiples of the motor orders (np) with spectral content above 2,000 Hz, the order 4*np reaches the largest amplitudes. A gear box order (gp) is close to np. While the other loudness during the runup remained significantly below that of the ICE powered vehicle, the sharpness was higher, as shown in figure 4, due to the high-pitched 4*np and 8*np tones. More representative than sharpness however, were tonality measures such as tone-to-noise ratio (TTNR) and prominence ratio (PR).

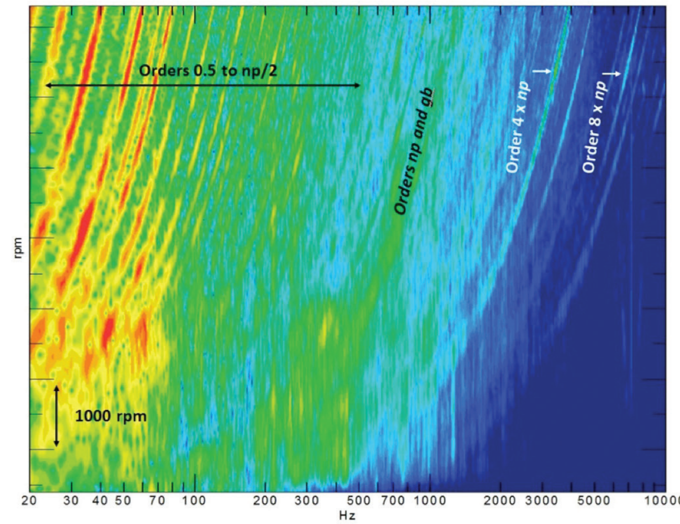

Figure 3: Electric vehicle run-up spectrum.

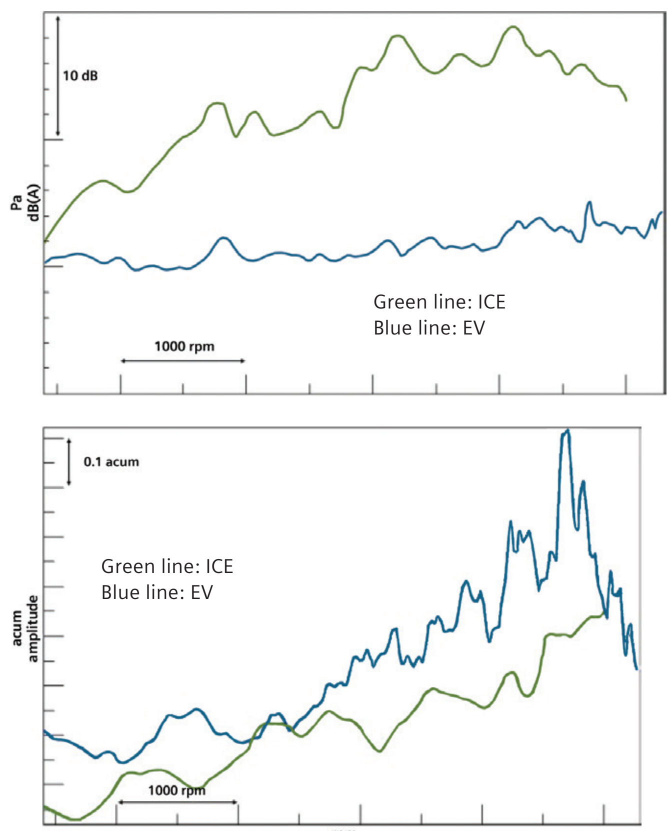

Figure 4: Run-up metrics loudness (up); run-up metrics sharpness (down).

Transfer path analysis revealed the 4*np content to be essentially air-borne in the affected frequency ranges, indicating that the best solution was the use of dedicated and selective sound packaging material while there was opportunity to lower the overall body's weight, of course within the constraints of strength and safety. For this purpose, a noise target was designed based on the response spectrum, as shown in figure 5.

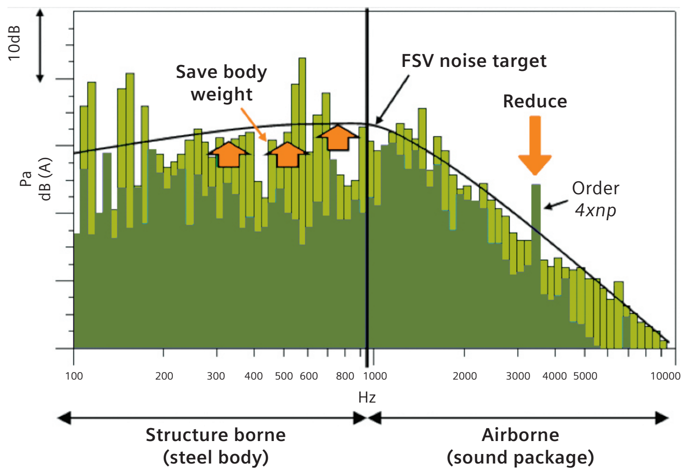

Figure 5: Comparison of EV and ICE noise responses to allow spectral target setting.

As a result of this exercise, it was concluded that significant weight savings could be achieved with clever designs due to the quieter drivetrain in an electric vehicle by relaxing the NVH upper target limits in the frequency range less than 1,000 Hz. For example, body noise transfer functions (NTF) between motor mounts and passenger compartment could have an upper limit raised without impairing the platform NVH targets. On the other hand, the high-frequency pure tone noise generated by the electric motor poses a problem that will need dedicated measures, for example, selective absorption material. It was expected that a three decibel (dB) noise reduction from the prominent frequencies could be obtained for a penalty of around one kilogram (kg), which is insignificant in comparison to the weight savings elsewhere in the sound package. An in-depth discussion can be found in the SAE paper. [2]

Receiver

Perception aspects as well as specific annoyance observations constitute the requirements placed on the NVH performance of HEVs. This means that despite the lower noise levels of electric powertrains, acoustic engineers will face challenging times in order to address these expectations. Because of the lack of masking effect of the combustion engine noise, multiple whistling high-frequency tones and other subjectively unpleasant noises will emerge and create a sensation of uncontrolled harmony. Also at idle, the noise of accessories such as the air-conditioning compressor, power steering pump, vacuum pump, and fans will be quite prominent and may have a very tonal character.

Besides pleasantness, the dynamic impression of the interior noise is also an important feature in the design of a brand-specific sound. Since the load dependency of the interior noise in electric vehicles is generally lower than ICE vehicles, they may be perceived as less dynamic, which does not really fit with the well-known quick and strong torque build of the electric motor.

Contrary to conventional vehicles, the driving condition is often decoupled from the operation state of the ICE. For example, the combustion engine can run at constant speed while the vehicle is accelerating at full load. Even more remarkable is the frequent start/stop of the ICE and upcoming whine noise during regenerative braking. These unexpected phenomena in hybrid vehicles may cause disorientation for the driver. Automotive design teams will henceforth have to face these problems and design a brand sound that satisfies customer needs.

An example (2): Electric vehicle pedestrian alert system

An NVH topic that is increasingly considered as a critical noise issue for HEVs is the relation between the exterior sound of quieter road transport vehicles and the safety of vulnerable road users (VRUs). In particular at low speeds, before the tire noise becomes observable (less than 20 km per hour), the absence of any perceived engine noise, and hence the absence of any recognizable vehicle proximity warning, may cause danger to other road users.

Since this topic ultimately should be translated into a design requirement for a vehicle, and hence be addressed in the standard vehicle engineering process, standard software tools to enable and support such design tasks need to be provided. Two major challenges are addressed in this paper.

The first challenge involves the psycho-acoustic design and synthesis of a suitable warning sound for VRUs that is detectable and locatable, and that can be recognized as a vehicle while causing minimal annoyance to the community. This challenge requires research into the exterior sound perception domain itself, the analysis, relevance assessment, modeling of the various sound components and the synthesis of target sounds, allowing parameterized evaluation studies to be carried out. An example of the noise signature of a Nissan Leaf public dataset is shown in figure 6.

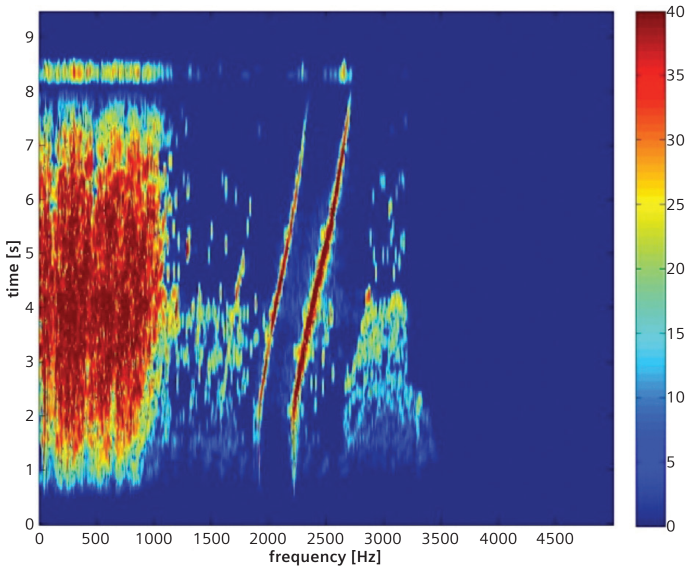

Figure 6: Electric vehicle warning sound spectrum (0-20 km/h).

From figure 6, two signal contributions clearly stand out. The first contribution component consists of broadband low-frequency content with a peak at 600 Hz and an important contribution up to 100 Hz. An additional broadband group is found in the range between 2,800-3,500 Hz. The second contribution features a purely harmonic content with speed-dependent frequencies. Two groups are found: a first dominant group with two nominal frequencies at 2000-2200 Hz and a secondary group with three nominal frequencies 1,100 Hz, 1,350 Hz and 1,600 Hz, active particularly in the first part of the measurement window. For the various signal components, furthermore, a modulation study was performed by means of an envelope spectral analysis diagram for amplitude modulations and some narrow-band spectral analysis for FM sidebands. [3]

The second challenge relates to the optimal configuration design of the sound source(s) on the car to reach maximal warning effect with minimal annoyance outside the danger area. Simulation methods for the sound propagation, covering a wide frequency range and taking vehicle and environment constraints into account, are instrumental for this. The assessment criteria must support complex sound fields that include ambient (masking) noise (for example, from other traffic and the surrounding environment), a real vehicle environment, a real road environment, and others. This will also require making the step from numerical calculation to, ultimately, the actual sound synthesis at the receiver location for assessment studies.

In order to illustrate the scenario above, a number of acoustic simulations have been performed at a concept stage. The directivity of the source and level of noise in the vicinity of the car can easily be assessed for different configurations, leading to optimal configuration and enabling the derivation of component and sound system specifications. Different approaches exist, including the multipole boundary element method and the ray tracing method. In this document, the noise has been computed using a Simcenter 3D™ Boundary Element Method (BEM) approach where the scattering surface of the vehicle has been discretized using 2D elements. A representative car model was used. A refined microphone array was defined in front of the car to capture the emitted noise. A symmetry plane took

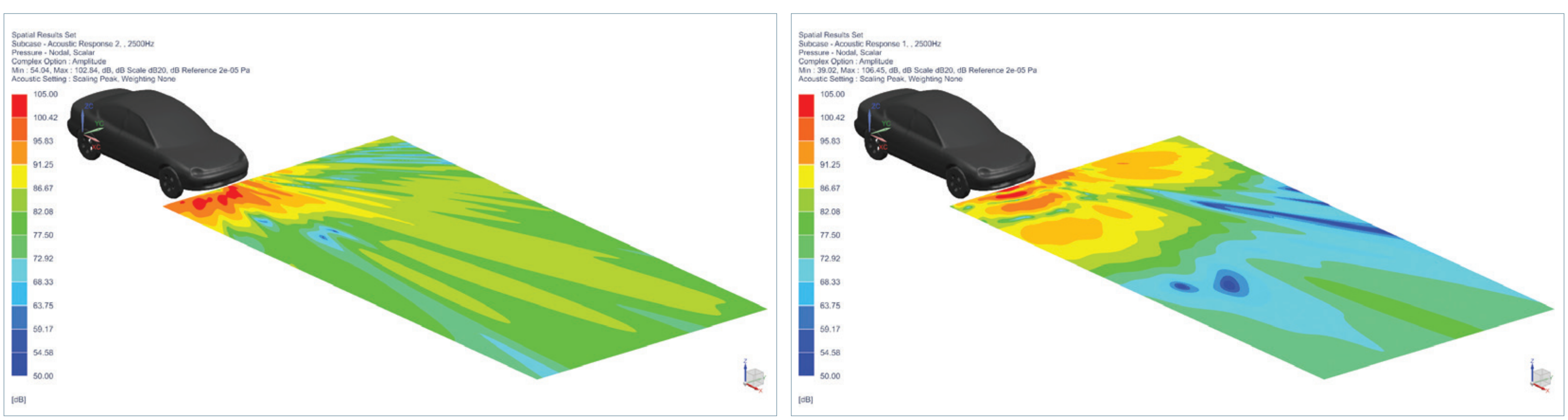

Figure 7: Sound source positions at 2,500 Hz of right wheel housing (left) and extreme right bumper (right).

into account the road surface reflection. A 100 dB monopole with unity amplitude was defined to model the source. Due to the size of the acoustic mesh, an advanced BEM solver has been used, known as fast multipole BEM. Some typical results for two sound source positions (firewall and wheel housing at 2,500 Hz) are shown in figure 7.

Additionally, the same technology can help make decisions as to whether sound will penetrate complex traffic situations, ensuring that the sound is audible in key locations where pedestrians might be expected to be present, such as between parked vehicles on the side of the road. The example in figure 8 shows that for a given source position, noises at 650 Hz and 2,500 Hz would not be audible to the same degree in the same location, an important consideration when designing the warning noise itself.

The above simulation methodology is instrumental for a proper configuration design of the sound source(s) to reach maximal warning effect in the danger zone with minimal annoyance for the environment or other traffic users. In order to perform the study of the actual sound perception, the sound simulation must be linked to the source signal design and interpreted in terms of subjective perception and alert/warning level by actual listening tests.

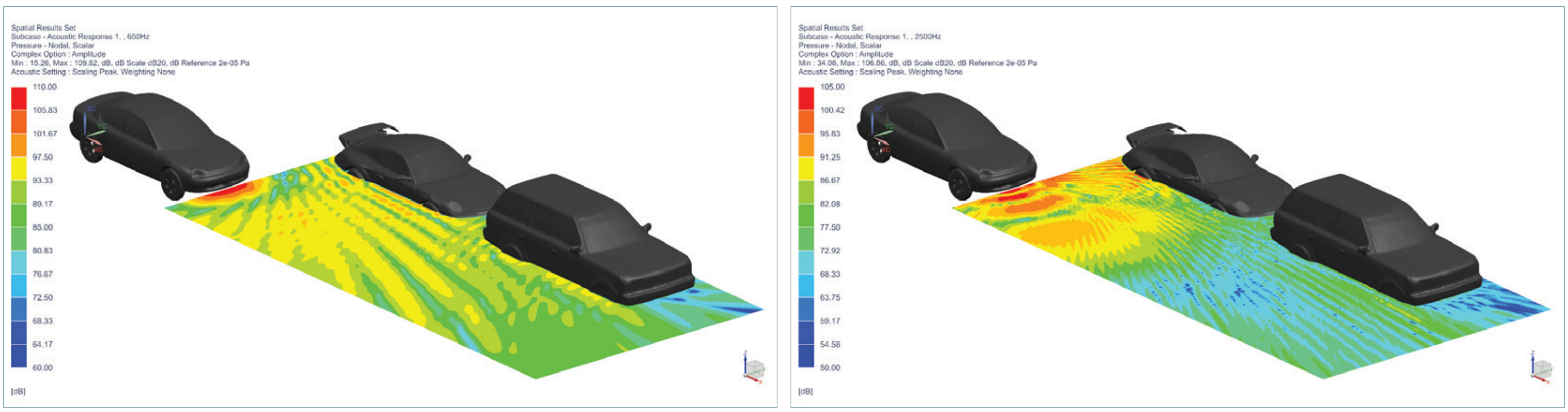

Figure 8: Directivity analysis for 650 Hz (left) and 2,500 Hz (right).

Conclusion

This research study addresses some of the major elements in the hybrid and electric vehicle-related NVH engineering process. It demonstrates that a number of new challenges emerge when compared to ICE-powered vehicles, thus requiring not only specific technical solutions but also adapted and novel engineering, testing, and simulation methodologies. In hybrid and electric vehicles, auxiliary systems such as battery cooling (fan) and transmissions generate high-pitched noises that are unmasked at low speeds. At the level of sound transfer, a major impact results from the high-frequency nature of the noise sources, aggravated by the tendency for vehicle weight reduction. Classical NVH methods such as TPA and trimmed-body acoustic simulation are extended to deal with the corresponding higher frequency ranges. At the receiver end, much more emphasis is put on the subjective appreciation of the sound. In order to enable the proper identification of the sound quality problem of the underlying sources and transfer paths, and hence the engineering of solutions through a model-based approach, a high-performance and physically relevant sound synthesis approach must be developed. Another important topic that appears with the design of hybrid/electric vehicles is suitable compensation for the absence of exterior sound at low speeds. The proposed approach is to equip quiet vehicles with an artificial warning sound emitted during vehicle operation to alert the traffic users of the vehicle's approach, trajectory and speed.

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