EXAMINING THE NVH CHALLENGES POSED BY HYBRID AND ELECTRICAL VEHICLES

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1 INTRODUCTION

The demands for greener transport have over the last years resulted in a large variety of new powertrain and vehicle designs. Powertrain electrification is one of the key enablers for the future automotive industry in order to reach lower CO2 emission targets. This involves the use of new system concepts with characteristics, performances and constraints which are largely different from these of combustion-engine driven vehicles. This also holds for the NVH behavior, although electric vehicles are significantly quieter an equivalent ICE powered version, their interior noise is marked by high-frequency tonal noise components with multiple coupled or independent base frequencies which can be subjectively perceived as annoying. The power electronics, and more particularly the Pulse Width Modulation control, cause specific sound modulation patterns. Traditional broadband sources like wind or tyre noise but also other disturbing noise shares from other components (e.g. oil pump, HVAC system, battery fan, alternator, transmission systems) are no longer masked by combustion engine noise and give rise to complex sound signatures. With lightweight design stretched to its limits to maximize driving range and performance while moderating battery cost, achieving acceptable NVH performance becomes a greater challenge.

Besides this also, the influence of electrification on vehicle exterior noise is widely discussed. On the one hand, electrification is seen as a chance to reach a significant reduction of environmental noise pollution. On the other hand, there is the risk that quiet vehicles are not perceived by pedestrians and other vulnerable road users (blind people, etc.) as well as ICE vehicles, creating a dangerous situation. This challenges automotive OEMs with the design and engineering of vehicle approach warning sounds that ensure pedestrian safety while minimizing community annoyance.
The new challenges posed to the interior NVH behaviour and exterior sound of HEV were clearly stated by several OEM and suppliers at the 2010 SIA Conference on "NVH of Electric and Hybrid Vehicles" [3]. The increasing complexity of the NVH problem is summarized in Figure 1.

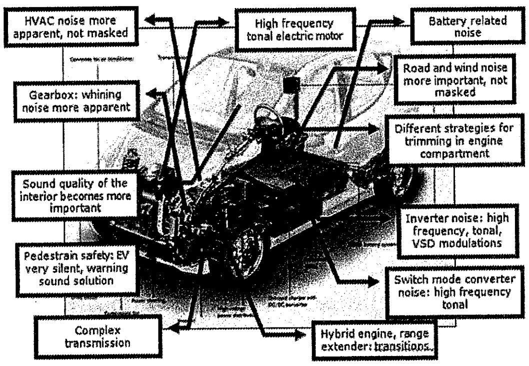

Figure 1: Summary of HEV-NVH challenges (SIA 2010)

Over the last decade, the Source-Transfer-Receiver model has been adopted as one of the most useful methodologies to address the NVH design engineering problem, hence it is of interest to assess how well this model addresses the HEV-NVH challenge and where innovation is (or needs to be) introduced. This paper addresses this problem following a source-system-receiver approach with concrete case studies

2 HEV-NVH FROM THE SOURCE-TRANSFER-RECEIVER VIEWPOINT

2.1 Source Level

Since the engine is a major noise source in conventional vehicles, the level of the noise generated by HEV is significantly lower due to its absence [1]. The signature of the noise is however different and generally a lot more complex. Some striking differences are discussed below.

First of all, HEV feature new source components such as the electric engine(s), power electronics, etc., these have completely different operational and noise characteristics than those encountered in conventional engines. Very characteristic as well are the modulation phenomena caused by the Variable Speed Drive (VSD) invertor which uses a Pulse Width Modulation (PWM) technique for controlling the rotational speed of the electric motor. The VSD modulations expose a typical "fan-shaped" harmonic structure in the noise footprint, composed by one or multiple central carrier frequencies surrounded by pairs of engine speed dependent side bands [8]. Typical are the high-frequency tonal components caused by the magnetic fields during electric driving and regenerative braking [1, 4, 5]. These are perceived as unpleasant whining or whistling noise in the vehicle interior [6]. A typical noise source signature measured inside the engine compartment of an electric vehicle is shown in Figure 2. One can clearly distinguish the high frequency motor harmonics as well as the power electronics modulation patterns.

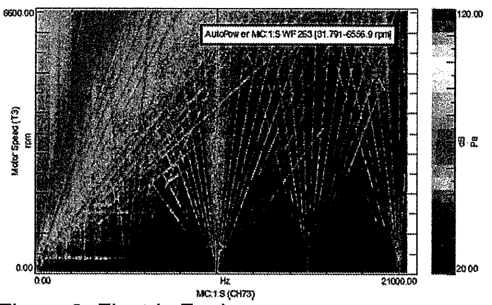

Figure 2: Electric Engine spectra

Due to the missing masking effect of the ICE, the noise shares of several other source components such as the transmissions, HVAC system, aerodynamic noises of the battery cooling system, oil/water pump, tyres etc. become audible [1, 7]. These noise shares can be very disturbing and must be included in the analysis.

Challenging as well for hybrid vehicles are the transient phenomena, such as the extremely fast, almost abrupt changes of the engine speed during full load acceleration [1]. In addition, large amplitude variations of the electric whine noise occur during vehicle acceleration and braking [4], making the signature analysis even more difficult. Typical examples are the frequent start/stop operations of the combustion engine in hybrid vehicles [5, 9] and the switching noise of the power cooling unit [1].

Taking all these elements into account, one can clearly state that the noise signatures of HEV feature a higher level of complexity that cannot be handled by the existing signature analysis techniques developed in view of ICE engines of which the noise is dominated by a limited set of low-order harmonic components related to a single RPM. Adapted methods are needed to deal with the 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 in particular in transient operating conditions.

2.1.1 Switched Reluctance Motor Simulation

As an example of the source challenges, the case of the NVH simulation of a switched reluctance motor (SRM) is discussed. An SRM is a type of synchronous machine, but with particular features: the stator windings make use of field coils, but no coil or magnetic material is present on the rotor. The result is a very robust design, which is simple to manufacture and avoids the use of rare earth materials otherwise needed for permanent magnet motor variants. Establishing a model for such motor requires a multi-physics simulation approach. This was applied to the concrete case of a 12/8 SRM to be used in an integration study for both FEV and HEV systems, covering the vehicle thermal management and NVH properties. Figure 5 shows the modeling workflow.

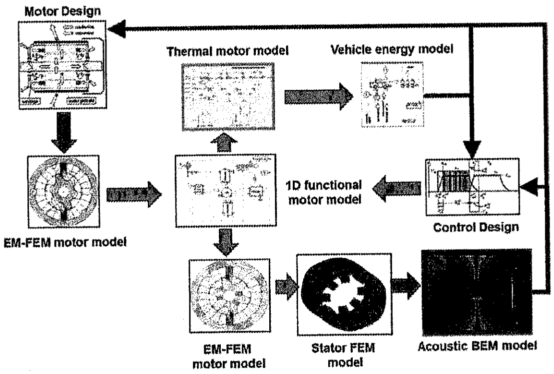

Figure 5: SRM modeling workflow

This process starts with a 2D electromagnetic motor model, which in turn is used to create a 1D functional model. The functional model can then be used to derive the acoustic properties as well as a vehicle thermal model [10].

Functional Model

There are solutions available for the analytical modeling of the SRM, but a more detailed and precise model can be obtained by the use of look-up tables containing the non-linear inductance profile and other important magnetic characteristics. As such look-up tables gave the best results overall, they were chosen to represent the SRM system. To obtain the magnetic characteristics for this virtual model, a 2D electromagnetic finite element model was used. This model allows extraction of magnetic flux and torque for a given rotor angular position and current. This procedure is repeated multiple times to obtain flux and torque data for a discrete range of current and rotor position values that cover the whole operating range of the SRM. Once the look-up tables are obtained, the complete functional model can be implemented. This model covers the SRM and its look-up tables, but can be complemented by detailed models for controls, power electronics, loads, activation angles and losses. The 1-D functional model was built in LMS Imagine.Lab AMESim, integrating different physical domains. Figure 6 shows the 12/8 SRM system with 3 half-bridge converters and angle control.

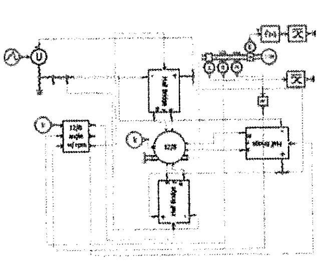

Figure 6: 1-D Functional model of the SRM

NVH Model

By using the detailed 1-D model, it is possible to calculate the phase currents and motor rotor position of a given working or load condition. This data can be used in the 2-D magnetic finite element model of the motor to determine the magnetic forces in the air gap that act on the stator. The magnetic forces acting on the stator teeth are surface density and volume density magnetic forces, but the latter can be neglected with respect to the surface forces. This procedure is repeated for each rotational position for one full rotation, for a motor operating in steady state conditions. The forces are then divided into x and y directions and are transformed to the frequency domain. Subsequently, the structural modes of the stator are calculated by means of finite element method. Figure 7 shows some structural vibration modes of the stator.

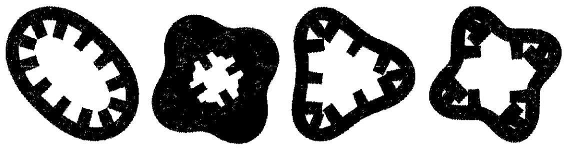

Figure 7: FE Modes 1-3-6-10

These vibration modes are used together with the magnetic forces generated previously to calculate a modal-based forced response, which consists of the surface accelerations of the stator based on the magnetic forces excitation. Finally, the calculated accelerations are the boundary conditions to be used with the Boundary Element Method (BEM) for exterior noise radiation prediction.

NVH Analysis

Finally, an acoustic prediction of the SRM was carried out for two working conditions. The phase firing angles are very important in the SRM torque production with respect to maximum and minimum current. For this reason they were chosen as parameters and their effect on the sound pressure levels produced by the motor evaluated. The two cases were chosen: firing angles optimized to maximize torque and firing angles optimized to maximize torque and minimize mean current levels.

In Figure 8, the sound pressure levels of the second simulation case are shown for a planar field point mesh of 1.2m x 1.2m at 1604 Hz. The average value of the acoustic pressure levels over a spherical field mesh around the stator as a function of frequency is shown in Figure 9 for both simulations. These results show a clear difference between the two cases. The minimization of the current has an important effect on the acoustic power response of the SRM. However, in some frequency ranges the system with minimal current has higher acoustic power levels. This happens because the current levels at that particular frequency band are higher, even when the mean current levels are lower for that case.

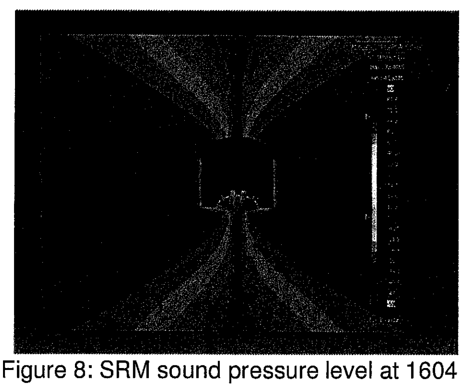

Figure 8: SRM sound pressure level at 1604 Hz

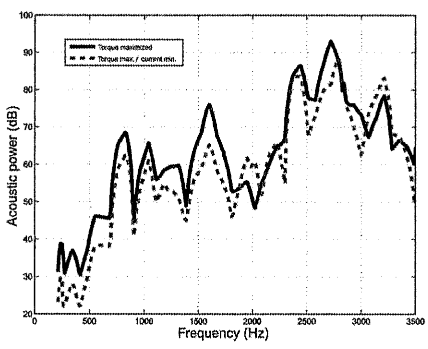

Figure 9: SRM average sound pressure level

2.2 Transfer Level

The radically changed noise source signatures of electric powertrains also pose different requirements on the methods and models describing the noise transfer from the different noise sources to the response or receiver point(s), for example the driver's ears. The main problem is related to the much higher frequency range of the sources implying reconsideration of the formulations that are used to describe and model (experimentally and numerically) the propagation.

The key experimental technology to be reconsidered in view of these HEV challenges is Transfer Path Analysis (TPA). TPA is an experimental NVH technique that allows identification of the structure-borne and airborne transfer pathways from sources to receiver based on operational data and FRF measurements. This method, developed since the eighties, has focused on the lower-frequency order components which are dominating in traditional ICE vehicles. HEV however pose new challenges. Firstly, TPA methods will have to be capable of dealing with the higher frequencies that play a more prominent role in HEV. The traditional TPA approach appears to break down at frequencies above a certain threshold, most likely because of the large variability of the Frequency Response Function (FRF) phase behaviour. This requires the development of energetic, power-based TPA formulations. Secondly, the complex source signatures of HEV face the pseudo-stationary frequency domain approach with applicability limits, requiring the development of time-domain TPA formulations [11]. Such time-domain approach allows auralization and sound quality analysis of the source-path contributions to the target responses.

Also on numerical simulation level, the challenge is to extend deterministic simulation methods for acoustic source-receiver transfer functions to broad frequency ranges. These methods have to support the rich (multi-frequency) tonal as well as broadband high frequency sources such that the results are compatible with auralization as needed for perception studies.

For the purpose of predicting deterministic acoustic source-receiver transfer functions, a spectrum of numerical field evaluation methods has been developed over the past decades. Each of these methods is more appropriate for specific applications or frequency ranges.

- Finite Element Method (FEM) – Recognised as the most suitable solution for interior acoustic field problems, recent developments regarding the incorporation of the radiating field towards infinity e.g. Perfectly Matched Layers (PML) [12] have extended the FEM capacity to include large exterior acoustic field problems..
- Boundary Element Method (BEM) – Judged to be most suitable for exterior acoustic problems, current research on enhancing BEM focuses amongst others on Rayleigh-based methods, such as the high-frequency Boundary Element Method and lumped parameter BEM, Fast Multi-pole methods [13]
- Ray Tracing method (RTM) is suited for addressing high-frequency problems as its inherent ray assumption breaks down at lower frequencies. Recent advances in Ray Tracing have primarily focused on improving the accuracy and applicability to arbitrary geometries and distributed source excitations.

When well employed, the FEM and BEM methodologies yield accurate results but even with the latest advances their applicability is limited to the low- and mid-frequency ranges. In contrast, the RTM is limited to the higher frequencies. At the moment a full-frequency range deterministic evaluation of the source-receiver transfer functions, which is required for the sound quality evaluation of HEV, also in view of the high-frequency tonal noise from typical HEV sources, is not available. However, it is expected that a frequency-hybrid approach, where FEM/BEM/WBM is combined with RTM that is updated with the most recent advances, is able to address this challenge.

2.2.1 Application Example 2: EV lightweight NVH design

The fact that EVs are in general quieter than their ICE counterparts offers car makers 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 electromotor developed by WorldAutoSteel [14-16].

Measurements were conducted on two small vehicles that both share the same body, one was equipped with an internal combustion engine (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 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 (3500 Hz when the vehicle drives at top speed). Figure 10 shows the (logarithmic) frequency spectrum during run-up. From multiples of the motor orders (*np*) with spectral content above 2000 Hz the order 4**np* reaches the largest amplitudes. A gear box order (*gp)* is close to *np*. While the overall loudness during run-up remained significantly below this of the ICE powered vehicle, the sharpness was however larger, as shown in Figure 11, due to the high pitched 4**np* and 8**np* tones. More representative than sharpness however, were tonality measures such as TTNR (Tone to Noise Ratio) and PR (Prominence Ratio).

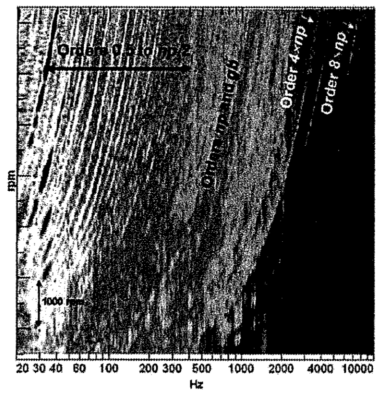

Figure 10: EV run-up spectrum

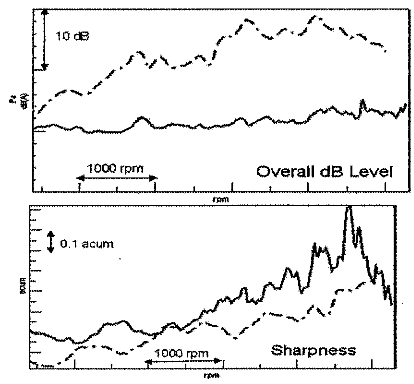

Figure 11: Run-up metrics. Upper: loudness, lower: sharpness. Full line: EV, dashed line ICE

TPA revealed the 4**np* content to be essentially airborne in the affected frequency ranges, indicating the best solution was the use of dedicated and selective sound packaging material while the was opportunity to lower the overall body structure weight, of course within the constraints of strength and safety. To this purpose, a noise target was designed based on the response spectrum, as shown in Figure 12.

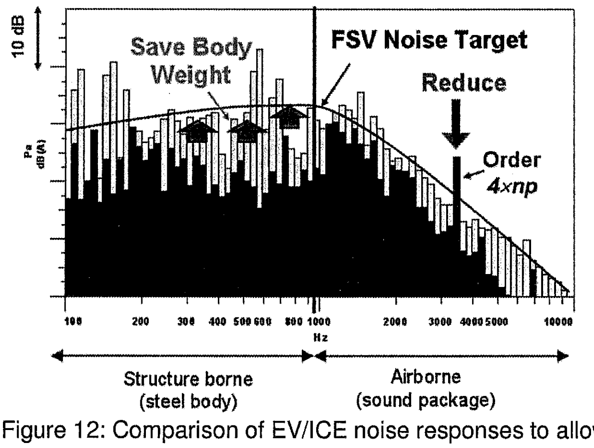

Figure 12: Comparison of EV/ICE noise responses to allow spectral target setting

As a result of this exercise, it was concluded that significant savings in body weight could be achieved with clever design due to the quieter drivetrain in an EV by relaxing the NVH upper target limits in the frequency range <1 kHz. For example, Body Noise Transfer Functions between motor mounts and the passenger compartment could have an upper limit raised without impairing platform NVH targets. The high frequency pure tone noise generated by the electric motor is a problem that will need dedicated measures, for example by selective absorption material. It was expected that a 3dB reduction of the prominent frequencies could be obtained for a penalty of around 1 kg, which is small in comparison to the weight savings elsewhere in the sound package. A complete discussion can be found in [16].

2.3 Receiver Level

In recent surveys, customers express a lot of expectations concerning sound quality of electric vehicles, but also fears. Some express the desire for more silence and sensations of "fluid driving". Others expect a modern, futuristic sound of a pleasant kind. Perception aspects as well as specific annoyance observations constitute the requirements put on the NVH performance of HEV. This means that, despite the lower noise levels of electric powertrains, acoustic engineers will face challenging times to address these expectations. There are several reasons for this. First of all, because of the missing 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 [2]. Also at idle, the noise of accessories such as the AC compressor, power steering pump, vacuum pump and fans will be quite prominent and may have a very tonal character [17].

Besides pleasantness, also the dynamic impression of the interior noise is an important feature in the design of a brand or market segment specific sound. Since the load dependency of the interior noise in electric vehicles is generally lower than in ICE-driven vehicles, they may be perceived as less dynamic, which does not really fit to the well-known quick and strong torque build of the electric motor [18].

Another important issue, specifically for hybrid concepts, is the unexpected and sometimes counterintuitive acoustic behaviour. In contrast to conventional vehicles, the driving condition is often decoupled from the operation state of the ICE [1, 7, and 19]. For example, the combustion engine can run at constant speed, while the vehicle is accelerating at full load. Remarkable as well is the frequent start/stop of the ICE and upcoming whine noises during regenerative braking. These unexpected phenomena in hybrid vehicles may cause a "disorientation" of the driver [2]. The automotive design teams will henceforth have to face these problems and design a brand sound that satisfies the customer needs.

2.3.1 EV warning sound projection

An EV-NVH related topic that has sprung to attention only very recently (since 2009) and which is increasingly considered as a critical noise performance for HEV, is the relation between the exterior sound of quiet road transport vehicles and the safety of Vulnerable Road Users (VRU) [20, 21]. In particular at low speeds, before the tyre noise becomes observable (< 20 km/h), the absence of any perceived engine noise and hence the absence of any recognisable vehicle proximity warning, may cause danger to the other road users.

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

The first one involves the psycho-acoustic design and synthesis of a suitable warning sound for VRU that is detectable and locatable, that can be recognized as a vehicle whilst causing minimal annoyance to the community. This requires research into the exterior sound perception domain itself, the analysis, relevance assessment and modelling 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 [23] is shown in Figure 13.

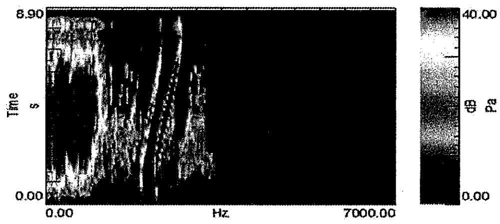

Figure 13: EV Warning Sound spectrum (0-20 km/h)

Two signal contributions can easily be discerned. The first contribution component consists of broadband low frequency content with a peak at 600 Hz and an important contribution up to 1000Hz. This could be the combined effect of the artificial low frequency contribution described in [22] and ambient noise. An additional broadband group is found in the range 2800-3500 Hz. The second contribution features a purely harmonic content with speed dependent frequencies. Two groups are found, a first dominant group with 2 nominal frequencies 2000-2200 Hz and a secondary group with three nominal frequencies 1100-1350-1600 Hz, active in particular 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. This analysis is discussed in more detail in [24].

The second challenge relates to the optimal configuration design of the sound/speaker 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 into account vehicle and environment constraints are instrumental for this. The assessment criteria must support complex sound fields that include ambient (masking) noise (from other traffic, surrounding environment etc.), a real vehicle environment, a real road environment etc. This will also require making the step from numerical calculation to, ultimately, the actual sound synthesis at the receiver location for assessment studies.

To illustrate this, a number of acoustic simulations have been performed for a concept case. 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 BEM frequency and time domain methods and the Ray Tracing method. In the present study, the noise has been computed based on a Boundary Element Modelling (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 into account the road surface reflection. A 100 dB monopole with unity amplitude has been defined to model the source. Results have been solved for 2 frequencies, 650 and 2500Hz, which according to [54] are within the most audible frequency ranges by human beings. Due to the size of the acoustic mesh, an advanced BEM solver has been used, called Fast Multipole BEM (or FMBEM), more dedicated to efficiently solve significant model size. Some typical results for two sound source positions (bumper centre, bumper extreme right, wheel housing right, firewall) are shown in Figures 14 (650 Hz) and 15 (2500 Hz). More simulations were conducted for sources at other positions allowing an optimization design and are discussed in detail in [24].

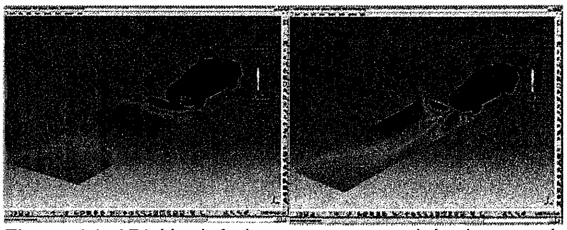

Figure 14: 650 Hz, left: bumper centre; right: bumper left

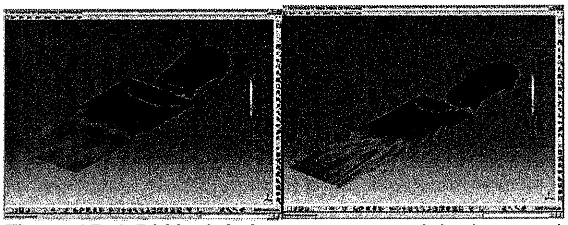

Figure 15: 2.5 kHz, left: bumper centre; right: bumper left

These methodologies, which have proven their usefulness in pass-by-noise simulation, are hence shown to be 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 has to be linked to the source signal design and interpreted in terms of subjective perception and alert/warning level by actual listening tests. To realize this, the frequency domain BEM noise transfer functions can be transformed into time domain filters as is applicable also in pass-by-noise testing [11]. This approach is actually a time-domain equivalent of the source contribution analysis methodology derived from Transfer Path analysis.

3 CONCLUSIONS

This paper addressed some of the major elements in this Electric/Hybrid NVH engineering process following a source-system-receiver approach. It was demonstrated that a number of new challenges emerge when compared to ICE powered vehicles, requiring not only specific technical solutions but also adapted and even novel engineering, testing and simulation methodologies.

An important element in the discussion concerned the electric motor causing a characteristic tonal and modulated sound, depending on motor type, its power electronics and the motor control which requires advanced signal analysis as well as multi-physics simulation approaches. Auxiliary systems such as battery cooling and transmissions generate high-pitched noises which are unmasked at low speeds. On 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 transfer path analysis and trimmed-body vibro-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. 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 is developed. A second 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 traffic users to the vehicle presence and trajectory & speed. The present paper investigates the related sound and sound system engineering requirements.

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