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New Challenges for Electric Vehicle Sound Enhancement Systems

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ABSTRACT

Automotive customers are used to benefit of in-cabin sound enhancement systems to have a better acoustic driving experience. For internal combustion engine (ICE) vehicles, the in-cabin sound enhancement systems are mainly used to adjust the native/original vehicle sound. In contrast, for battery electric vehicles (BEVs) the sound enhancement systems are responsible for the complete vehicle sound since the BEVs are much more silent by default. This creates new challenges for both the car manufacturers and the noise management software suppliers. A wide range of possible sounds, the high complexity and flexibility of the control part and a smart adaptation of the system during all the vehicle lifetime, are some key requirements that need to be fulfilled to completely design a coherent BEV auditory experience. This paper will describe the process to develop and design the sounds, control logic and a software solution set to create, implement, and tune a BEV sound enhancement system.

Keywords: *vehicle sound enhancement, EV sound design, vehicle acoustics, automotive development process.*

1. INTRODUCTION

In-cabin car acoustics is designed with a reactive development approach in mind; the native sound of the vehicle and its effects on the interior sound field are addressed by passive and active measures, both with the intention of improving - or even shaping or enhancing the sound experience of the passengers. Thus, in-cabin sound enhancement systems play an important role since they provide a variety of sounds that are consistent with the conditions and dynamics of the vehicle but may not need to be generated by a mechanical component (e.g., the engine).
During the era of ICE vehicles, the in-cabin car acoustics was inevitably designed starting from the native engine sound. With the advent of BEVs, established design approaches changed completely. Since BEVs hardly have an engine sound of their own, coming up with a vehicle sound design changed from an adaptive to a mainly creative task.
Enhancing an in-cabin sound is for both ICE vehicles and BEVs an integral part of the development and production of a car model. Active sound enhancement typically utilizes the audio system of the vehicle - amplifiers and loudspeakers - and therefore boils down to the adaption or generation of digital audio signals for the vehicle interior. Not only is the sound produced by the enhancement system crucial to the overall in-cabin sound development, but there is also an important technical dimension, as the sound must be processed and provided to the audio output hardware. Sound enhancement is therefore not just an addition, but an essential component of the whole vehicle's audio system.
The digital audio design commonly is implemented on embedded systems and firmly integrated into the vehicle electronics system, be it in a control unit, head unit, the audio amplifier itself, or another appropriate component of the vehicle architecture that is responsible for audio processing and output to its loudspeakers. Integration at such a deep level is necessary to be able to achieve required real-time processing as well as cost efficiency.
The following sections will be mainly focused on BEVs sound enhancement.

2. BACKGROUND

BEV sound enhancement opens a wide range of possibilities in terms of sound design both for its own control logic and the corresponding sound features. In order to achieve a responsive sound design, further input variables for the audio system are indispensable. These can

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be parameters for vehicle speed, pedal position, torque, drive modes, etc.

These signals increase flexibility of the way how the system can respond to different driving conditions which then leads to a more complex parameter assessment and a corresponding control logic, that needs to evaluate this increased set of car parameters provided, for example, via the vehicle's CAN bus signals. This means that with a control logic part capable to do so, now complex vehicle conditions can be used as triggers for sound features which can be designed depending on many possible combinations of CAN signal values. As a result, the sound design tools are also required to be highly flexible to support these new design possibilities. To show how easily the complexity of a BEV sound design can increase, we will use the order-based Engine Sound Enhancement (ESE) as typically applied to an ICE as an example here. For BEVs, instead of "order-based", the term "harmonic-based" is more appropriate since there is no generic signal to be used as synchronization signal (like the RPM signal for ICE). Different alternatives can be considered instead (e.g., the signals for electric motor RPM or vehicle speed) to indicate velocity and acceleration, giving the driver a likewise familiar acoustical user interface. However, these chosen EV signals need to be scaled and mapped by some control logic to generate an RPM like user experience. Also, for BEV sound enhancement designs, there is a significant need for randomization or changing sounds compared to ICE vehicle as the risk of creating repetitive and thus boring, disrupting, or even annoying sounds is higher. This further increases the control logic design complexity. In terms of sound features, the options that fit with BEVs are very wide. In addition to the harmonic-based sound as the main sound feature, WAV players, noise generators, granular synthesizers, etc. are often used by sound designers to effectively create BEV sounds.

Apart from the design itself, it is exactly this freedom on developing "any" sound for BEVs that also creates challenges both from a vehicle perspective as well as a sound design software perspective. From a vehicle perspective, the desired sound for the vehicle needs to be identified, from a software and tool perspective, the most flexible environment to enable the sound designer to create whatever is requested need to be provided. Moreover, the sound that is intended to be assigned to a specific vehicle in a preliminary stage of a project, typically is a concept sound that needs to be reasonably deployable during series production and usable in the final vehicle. The earlier there is the possibility to experience the fully deployed sound, the earlier it can be adjusted, if needed. Experiencing the sound in a car is important to adjust it appropriately, both depending on the environment (e.g., the vehicle cabin that is maybe still receiving adjustments) and the "real" dependency on driving conditions (vehicle dynamic properties).

3. SOFTWARE CHARACTERISTICS FOR THE DESIGN OF COMPLEX BEV SOUNDS

Another challenge to achieve and manage the crucial aspects described above is the interaction with the vehicle, the differentiation of driving conditions, how the sounds are applied and how the driver perceives them. This means that a close link between software development, prototyping and tuning of the BEV enhancement sounds is required. Therefore, the software environment needs to include the following capabilities beyond the embedded real-time processing capabilities to reduce the overhead associated with traditional embedded vehicle software development:

1. Sound prototyping
2. Realtime and in-vehicle SW testing and validation
3. Flexible yet robust signal flow changes without embedded SW re-validation (e.g., during the tuning phase)
4. Flexible and efficient signal flow changes after Start of Production (SOP) without embedded SW re-validation

Capabilities 1 and 2 are required in a very early project phase, when the target hardware (HW, control unit a.k.a. radio, satnav, amplifier) is typically not yet available even though the access to the vehicle signals (e.g., via CAN) as well as the possibility to drive audio outputs need to be supported. This, for example, can be achieved through a PC-based SW tool by using a CAN interface device and a soundcard. Capabilities 3 and 4 are key requirements during the late project development phase when the target HW is already available, and the embedded SW already integrated in the HW. Modifications of the embedded SW typically requires lengthy and costly test and validation and should therefore be avoided. As an example, the following section highlights a sound design process for BEV sound enhancement, for which the sound design software **m|klang® e** from Müller-BBM Active Sound Technology GmbH has been used. The focus of **m|klang® e** is to generate active and controllable sounds for automotive applications. It uses various inputs (e.g., CAN bus data, microphones) to generate an acoustic output signal that can be integrated with the vehicle's infotainment audio stream.

The product consists of different software components (Figure 1). The main parts are the Scratchpad including the Tuning Tool, used in the following sections and the embedded software. The Scratchpad is a tool for sound design, tuning and PC-based sound simulation. Its graphic user interface provides the necessary functions to create a signal flow using a large range of design, staging, and logic elements specifically developed for digital signal processors (DSPs) in automotive applications. The embedded software is the part that will be integrated into the production hardware of an audio system, e.g., radio head unit, audio amplifier, etc. Its scale of sound generation capabilities corresponds to the objects that can be used in a signal flow within the Scratchpad.

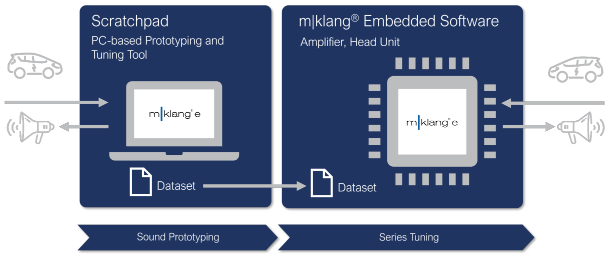

Figure 1. MBBM m|klang® e SW components. The *Scratchpad* and the *Embedded Software* are two separate parts. They share the *Dataset* that includes the signal flow and the tuning parameters; it is created by the *Scratchpad* and then used by the *Embedded Software*.

The link between the two environments is the *Dataset*. The sound designed and tuned is compiled in the Scratchpad, creating the *Dataset* that is then used by the embedded software (Figure 1). Because of this, it is not needed to change the integrated embedded software in case the signal flow and/or the tuning parameters change, since they are both included in the *Dataset* that is flashed on top of the embedded software.

Nowadays in the automotive industries the electronic platforms are developed independently of vehicle platforms and need to serve a broad range of them. The embedded software, used in combination with such an electronic platform, thus needs to be flexible enough to generate a wide range of sounds that can serve all those vehicles. So, the specifications for such a system can just consist of sound features that are used as building blocks for vehicle sound design. To create sound features enabling a fully flexible design and sound, the following steps may be completed during the development of a platform lead vehicle. First, a prototyping phase will define the functions required and test the concept in the vehicle. Next, the integration of the embedded software library into the audio system hardware is completed. Finally, the creation of the signal flow for series production and the final tuning can be done. The ability of the SW to follow the complete development chain ensures that the designed sound can be smoothly ported from one development step to the other and required changes that may arise during these phase transitions can be incorporated or corrected without unnecessarily disrupting development schedules.

4. USE CASES: BEV SOUND ENHANCEMENT SOLUTIONS

For BEV sound enhancement, different use cases can be considered. As previously mentioned, in this field there is a wide range of possible design spaces, and different customers have different needs. In some cases, the customer may be more focused on preserving a branded sound characteristics from an already existing ICE vehicle, sometimes the customer wants to design a completely new concept sound for a BEV.

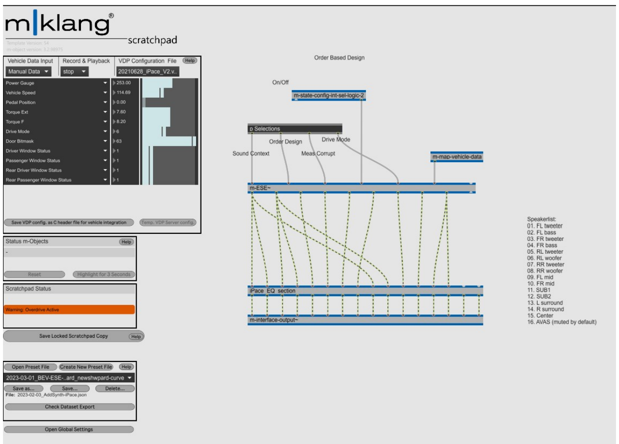

Figure 2. MBBM m|klang® e Tuning Tool. In the left area, the vehicle data interfacing can be set. On the right side an example signal flow with different linked objects is shown.

To meet different customer needs, the design tool needs to be modular. This ensures that multiple sound features can be designed separately and be later combined to create the final desired sound. Figure 2 shows an example of a simple signal flow designed with the MBBM **m|klang®** e Tuning Tool; in this example two different sound features have been designed separately (in different sub-modules called *sub-patcher*s) and then combined using mixing objects. The final stage applies different equalization parameters to different channels depending on vehicle signals and then routes them to the output channels. Thanks to the modularity of the Tuning Tool this is just one of the multitudes of possible combinations that can be created; other sound features can be designed and used, the sound features can be combined in a different way, the number of used sound features can be increased, different sound features can be routed to different channels etc.

In this section some use cases are described; the complexity of the sound designs increases from case to case. Starting from a pure harmonic-based sound design for BEVs, adding new features specifically designed for BEV, and then introducing the Triggered Sound part, that can be applied to the previous scenarios. At the end of the section, a small remark on the resource consumption estimation for the described use cases concludes the discussion.

4.1 Harmonic-based sound for BEV

Design approaches for Engine Sound Enhancements (ESE) commonly originated from a rather trivial starting point in the ICE parametric environment. Usually, engine RPM is sufficient to capture enough information regarding engine order behavior to then enrich it with desired sound components. The approach is considered mainly order-based, and the sound designer should mostly pay attention to the generated order shapes and dependencies from other signals and vehicle conditions amplitude-wise. Harmonic-based sound design would therefore be adjusted and fitted, e.g., through dedicated amplitude factors to aim for the desired order sound composition. Figures 3 and 4 show respectively an example of an order-based sound enhancement for an ICE vehicle and the corresponding results. In Figure 4 both the native engine order sound and its enhancement are depicted. The harmonic-based sound generation enriches the native sound characteristics of the car by adding orders. In the example, the result is a sportier vehicle sound thanks to the combination of its native sound and the generated orders. Although the control logic part is similarly easy to realize, the challenge for BEVs now is not just to enhance an order spectrum but to design it largely from scratch in the first place. For example, instead of simple narrowband spectral additions, the design of dedicated frequency shapes and harmonics now become necessary. Furthermore, another challenge now is the absence of the well-known combustion engine characteristics and gearbox behaviour in general.

Figure 3. Example of basic order design for an ICE vehicle. The GUI depicts an editor, showing five orders characteristics and their parameters. Each order can be adjusted independently, only the selected one (order 2.5) is highlighted.

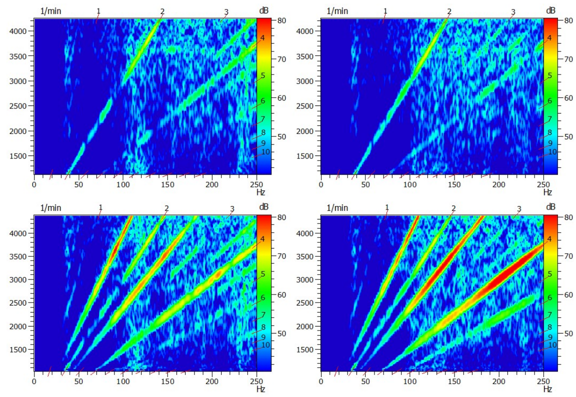

Figure 4. Engine order sound with the harmonic-based sound OFF and ON. Top. OFF: Baseline ICE vehicle sound for Front Left (FL) and Front Right (FR) seat positions. Bottom. ON: Order-enhanced ICE vehicle sound for FL and FR seats positions.

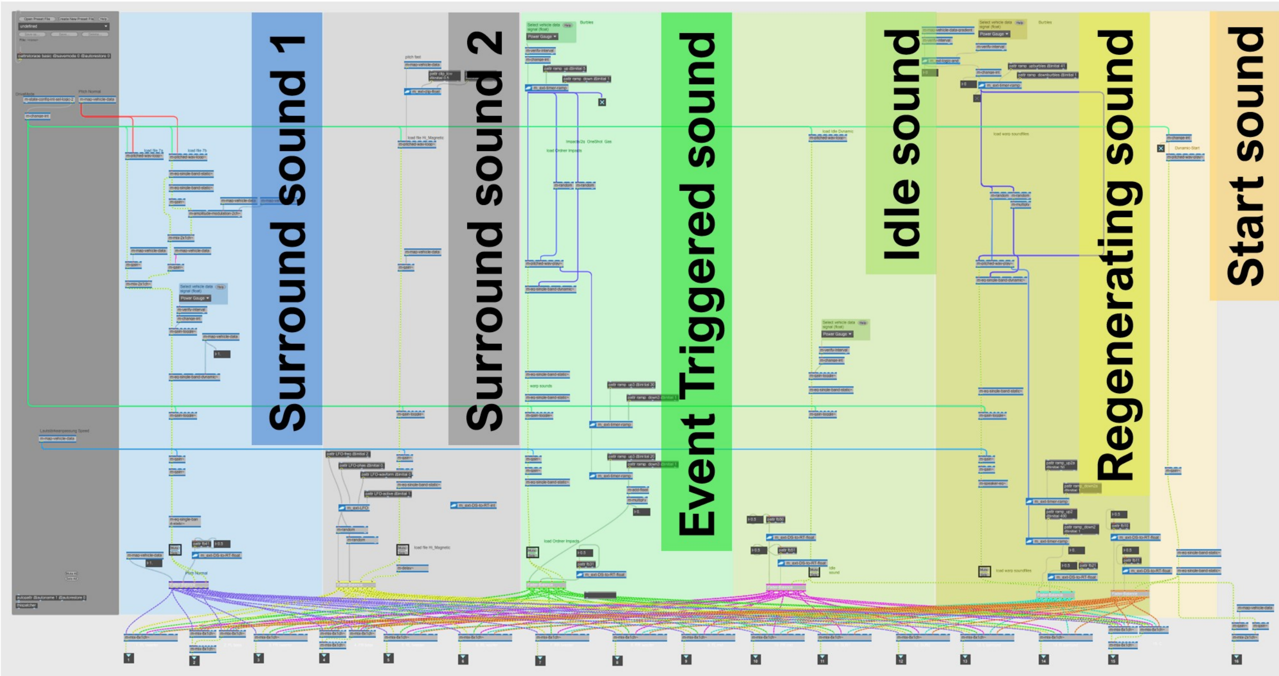

Figure 5. BEV sound enhancement design. Example of a sub-patcher that can be combined with other sections as shown in Figure 2. The use of the individual signal flow components of this sound design are highlighted.

For a BEV, engine RPM and torque are different and gear shifts are not necessary anymore. Hence as described earlier, for harmonic-based designs, a suitable synchronization signal needs to be parametrically mapped to generate useful values, which then enable for example a desired shifting-like sound behaviour.

4.2 Complex BEV sound enhancements

To expand the harmonic-based sound design to a more sophisticated approach, usually a higher number of vehicle states, conditions and behaviors are considered. In contrast to solely gearbox or transmission related behavior, the use of complex sounds expands the available sound design tools to a much more flexible and multidimensional range. The harmonic-based sound design methods can be viewed as rather technical and analytical because crucial aspects of the sound environment are largely pre-determined, for example due to the natively loud ICE noise environment which then needs to be tuned. Thus, quantifying and communicating the benefit of a harmonic-based sound result comes naturally by comparing order or harmonics spectra using a sufficient measurement regime (see for example Figure 4).

Regarding complex sounds, the design and tuning process additionally require a higher degree of creativity, because sounds to work with a BEV need to be “created” in the first place. Assessing a complex sound result with production partners and customers requires therefore a different way to communicate approval criteria. Furthermore, comparing harmonic-based and complex sounds from a technical side, the parameter space also increases and more control options like additional synchronization signals, driving modes, car states, etc. should be accessible by the designer to enable a responsive and dynamic sound design. This way the design spaces can be expanded to consider also states like energy regeneration and to aim for a distinct sound branding or further options to realize rewarding or engaging driving experiences The challenge for the software therefore is to be able to detect and interpret more control parameters of the BEV and to make them accessible in a meaningful way.

4.3 Triggered and event-based sounds

In addition to one-dimensional triggered audio like welcoming sounds, warning sounds, door triggers, jingles, and chimes, now designs based on events or car states are also possible. As triggered or event-controlled sounds can be applied to a multitude of car states and driving situations, the way to do so requires a sufficiently flexible and accessible control logic and condition management within the sound design software. If implemented congruently, this tool set then enables sound configurations, e.g., for energy regeneration, speed states, battery drain behavior, or even to virtually mimic ICE related gear-shifting or misfiring-like events. However, another challenge that comes along is that the more triggered sounds are used, the number potential repetitions in the auditory environment increases which quickly leads to subjective devaluation by the passenger. So further techniques like modulated trigger sounds, round-robin approaches, and options for randomization of audio characteristics are typically used.

Figure 5 shows a m|klang® e sub-patcher that is an example of a rather complex BEV sound design. It includes different sound sections: the surround sound is composed by two different sections that are driven by different CAN signals, additionally some event related sections are used to emphasize specific driving conditions that can be both one-time played event trigger sounds (e.g., Start sound) or sounds playing until a certain condition is met (e.g., Regenerating sound).

4.4 Resource estimation

A crucial aspect to be considered when designing any sound is its resource consumption of the embedded real-time software implementing the sound in terms of MIPS (Million Instructions Per Second) and memory. Especially talking about embedded systems, the total amount of available resources is strictly limited, so then the resource consumption of a specific sound design needs to be estimated to make sure it fits in the target HW. This is done during the sound and signal flow design phase and it is necessary to create a worst-case scenario in terms of resource consumption for the designed signal flow. In case of a pure harmonic-based sound it is quite easy to define such a worst-case scenario as it is limited by the maximum amount of available orders or harmonics that can be tuned, the maximum amount of amplitude factors that can be used and by the number of independent outputs. It's more difficult to identify the worst-case scenario when multiple sound features need to be combined as in the case of Complex Sound and Triggered Sound. So, another new challenge here is that the sound designer need to be aware of available hardware resources, meaning that there is a need to optimize their consumption during the sound design process, whereas the software tool should be able to perform reasonably reliable resource estimations even from an early project phase on.

5. CONCLUSIONS

In this paper some new challenges for BEV sound enhancement systems for active sound design have been described from the vehicle perspective and for the system and software, including the tool environment. Basically, the additional complexity of the desired/generated sound leads to additional effort in terms of sound definition, sound features availability, control logic availability and the actual creative design activity An additional challenge that is a direct consequence of all the abovementioned points is the increased effort for the tuning. On the one hand more complex sound features need additional engineering and design skills to be properly tuned, on the other hand the more the control logic part is extensive the more effort is needed for the tuning. For example signal thresholds need to be defined for each event triggered sound; all the calibration data need to be coherently tuned to perfectly describe the target driving condition that need to be modeled; new stages of quality approvals and sound branding assessments might become more necessary from a project management perspective; and the focus of the car interior being an actual sound stage will influence design decisions to a new degree of detail. A more agile development as supported by the flexible building blocks is crucial to solve the challenges of the complexity of BEV sound development for modern electronic platforms.

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