

Powertrain Sound Quality - Active Sound Technology Development and Deployment

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Abstract

Customer expectations on vehicle interior and exterior powertrain sound quality are rising from model year to model year. At the same time target conflicts in vehicle development have been increasing continuously in recent years due to strong market demands for powertrain downsizing and weight and cost reduction. In order to reduce or even eliminate difficult target conflicts the Active Noise Cancellation (ANC) and Active Sound Design (ASD) technologies turned out to be a powerful alternative to conventional (passive) NVH-countermeasures. As a consequence, the stringent NVH and sound quality targets can be met and hence customer expectations can be satisfied. The broad and robust deployment of Active Sound Technology on a global scale is a huge challenge in vehicle development. Here, an intelligent strategy and framework is mandatory, utilizing efficient and well-designed algorithms, development tools, methods and implementation processes. This becomes even more evident in light of an increasing number of product variants (complexity) and - in contrast to this - a decreasing number of prototypes. In this paper, selected aspects of the deployment of active sound technology for ICE-Powertrains will be discussed - e.g. with regard to complexity, pitfalls and tuning results. Finally, selected generic aspects and topics will be examined.

Introduction and Motivation

Starting with Paul Lueg's patent in 1936 [7, 3] on silencing disturbing sound oscillations by using an active acoustic system nobody would have imagined how far his idea has evolved until today. Over the last decades the technology has matured from an experimental laboratory setup to an application-ready-feature due to intense research activities.

The application of active sound-technology features in automotive engineering is highly driven by cross-attribute target conflicts. For instance, more and more stringent CO₂ fleet emissions by the EU challenge all OEMs regarding weight reduction. Moreover, cross-attribute target conflicts and cost pressure do demand for the deletion of conventional (passive) NVH-hardware countermeasures (e.g. due to removed balancer shafts [6]), but with an equal - or even improved - NVH- performance at the same time. Active Sound-based technology features are a key enabler to resolve such conflicts while maintaining an optimized NVH-performance (e.g. due to cylinder deactivation-driven issues on variable displacement engine-designs (VDE) [9]).

Beside the NVH-issue resolution by means of active noise cancellation (ANC), active sound design-technology fea-

tures (ASD) have gained more and more importance over the last years, e.g. due to PT-downsizing trends - in particular within the last two decades. Here, the extreme potential of ASD was proven in numerous vehicle applications due to its superior capabilities over passive methods (tuning flexibility, efficiency, robustness, etc.). ASD is a key enabler to satisfy customer expectations and brand sound-quality target requirements across OEMs.

In the last years, audio/infotainment-system-based active sound-features were introduced by many OEMs and were broadly applied within various vehicle lines [4]. This market trend is surely influenced by the rapidly decreasing cost of such systems, that is mainly driven by the quickly evolving embedded system architectures, e.g. increasing DSP-resources and capabilities, advanced DSP-chip topologies and level of integration (e.g. fully integrated System-on-Chip-Designs (SoC)) - as discussed in [10].

Within the next years both ANC and ASD are likely to become a 'standard'-feature across OEMs. What would Paul Lueg say today about his very simple but visionary idea evolving into so many nice technical application scenarios?! Well, we can be pretty sure that he would be as enthusiastic about it as we are...

Active Sound - Technical Overview

In this paragraph a short overview of active sound-based technology features will be given. Two example setups will be discussed: Setup 1 is a narrow-band ANC-feature that is based on an engine speed-synchronized Feedforward-controlled Narrow-band-ANC-algorithm (cf. [2]). Setup 2 is an active-sound-design-feature for internal combustion engines that is closely related to Setup 1. Both features are integrated in the vehicle audio/infotainment-system. Here, the basic functional principles and properties will be shortly summarized. Furthermore, selected critical aspects will be highlighted and discussed.

Active Noise Cancellation: A typical setup of an in-vehicle ANC-System (MIMO Narrow-band Feedforward-ANC) using the engine rotational speed [rpm] signal as a synchronization signal is shown in Figure 1. This setup was discussed quite frequently within literature (e.g. [1, 2, 5]). It shows the most important components of an in-vehicle ANC-system for PT-induced noise reduction, e.g. block diagram: adaptive filter algorithm (e.g. Filtered-X-LMS), in-vehicle ANC-feedback loop $S(f)$ and estimated secondary path transfer function blocks (SPTF: $S'(f)$).

The deployment and tuning of ANC-Systems is quite a complex task where several non-idealities and trade-

offs have to be considered. This is mandatory for the proper deployment in order to preserve an effective ANC-performance with minimized risk of failure modes at the same time.

The development and optimization of ANC-tuning parameters is an iterative process, which usually begins with upfront investigations - typically in early vehicle program phases. The ANC-tuning parameters ('Sound Profiles') mature across prototype levels and across vehicle program milestones. Here, potential ANC-failure modes due to uncertainty and vehicle-to-vehicle variability have to be avoided by a sufficient amount of verification work across all prototype levels.

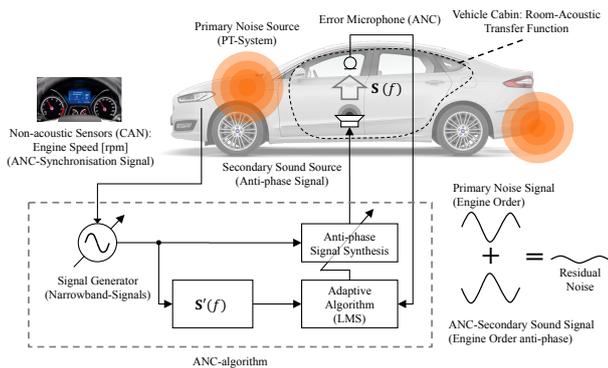


Figure 1: Functional principle and block diagram of an in-vehicle ANC-system for an internal-combustion engine application (Feedforward Narrowband-ANC): synchronization signal (engine speed [rpm]), adaptive algorithm, plant model $S'(f)$, actuators (loudspeaker) and error sensor (microphone).

Active Sound Design: Figure 2 depicts a block diagram of the ASD-System using an open-loop/'playback'-only approach that is attractive for OEMs due to reduced cost as it requires less hardware periphery. Here, a harmonic-sound synthesis algorithm is used - depicted as parallel-wired sine-wave oscillators with freely selectable order index value. Tunable sound synthesis parameters are e.g. engine order index, order phase offset, dynamic gain factors $a_1 \dots a_n$ and engine-speed-dependent engine order level look-up tables. Common non-acoustic input control signals are e.g. engine speed, accelerator pedal position and engine torque. Other input signals are possible of course. Typically, these are delivered via the CAN-network of the vehicle.

The synthesized sound signals have to be presented in a plausible manner in the vehicle cabin. Here, a set of perceptual requirements has to be formulated that have to be fulfilled by the ASD-system. For example, the ASD-synthesis algorithm needs to account for human sound localization effects and to control the spatial presentation of the secondary sound contribution. Audio/infotainment-related features can be easily adapted to the requirements of an ASD-system. Various signal processing-methods are used across ASD-system suppliers that all have their advantages and disad-

vantages. 3D-audio rendering algorithms can potentially bring further benefits due to the improved tuning potential, e.g. as soon as very complex sound designs are required. However, 3D-rendering algorithms might demand for a higher tuning effort.

Mixed setups of ANC and ASD are possible of course - using a pure closed-loop approach for ASD as well or a combined closed- (ANC) and open-loop approach (ASD). However, ANC and ASD cannot be considered as separated items when it comes to creating a sound design, since noise cleaning by means of ANC is an integral part of the sound design process.

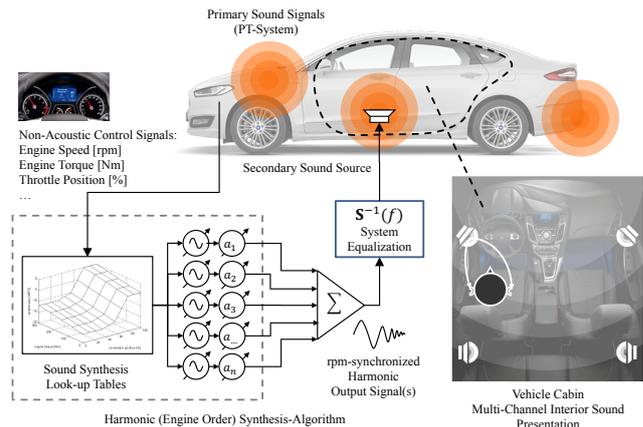


Figure 2: Functional principle and block diagram of an in-vehicle active sound design-system for an internal-combustion engine application: open-loop approach, input signals (CAN), engine order synthesis-algorithm, audio system/loudspeaker equalization stage $S^{-1}(f)$, (spatial) interior sound presentation

Vehicle- and System-Complexity

Vehicle model and system complexity both have a major impact on the vehicle characteristics (acoustic and non-acoustic). The resulting implications have to be considered carefully as soon as active sound-features have to be tuned and deployed. The tree chart as depicted in Figure 3 shows some (potential) impact factors for a single vehicle line as an example (i.e. an CD-Car limousine model with Diesel PT). Relevant vehicle- and system-features have been identified a priori by engineering judgement based on available vehicle, system and component data, measurements or based on simulation methods (CAE) for instance (vehicle system analysis task). These impact factors (vehicle features) generate a fair amount of effective tuning variants (here up to 16 variants as a worst case scenario for instance). Only a selection of possible impact factors are shown here, but others are possible as well of course. Here one important question is, whether these impact factors have a significant effect on the amount of the sound profiles. Furthermore, it is important to clarify whether these effects can be properly isolated from each other so that they can be down-cascaded into smaller sub-problems with easier manageability. Therefore, the impact factors and the resulting effects need to be well-

analyzed and understood. The tree chart can be divided into two main-categories - namely the vehicle *underbody-related complexity* and the *upperbody-related complexity*:

Underbody-related Complexity: The underbody-related complexity considers features such as engine variants and transmission/gearbox variants for instance. These features are related to the characteristics of the primary sound source which can potentially require differing ASD-engine order-profiles (e.g. due to differing primary sound properties, dynamic behaviour, etc.). This might also hold true for the ANC-profiles.

Upperbody-related Complexity: The upperbody-related complexity considers features such as body style-versions, steering wheel position and audio system-variants for example. These features have an impact on the electrical and acoustic properties of the secondary path transfer functions both for ANC and ASD. The corresponding SPTF-datasets need to be measured and to be included in the ANC- and ASD-profiles. Here, a certain amount of vehicle samples has to be measured to account for vehicle-to-vehicle variability in order to ensure for a robust performance with a minimized risk of failure modes.

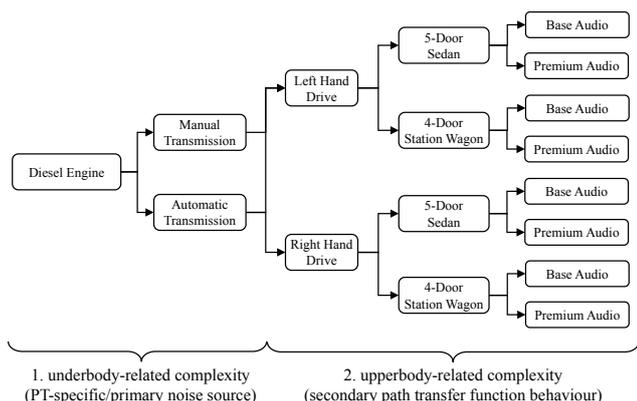


Figure 3: Vehicle-related complexity: Example scenario of relevant vehicle variants that (potentially) require a dedicated set of tuning parameters ('Sound Profiles') due to impact on acoustic vehicle- and system-characteristics.

Tuning- and Deployment-Process

In this paragraph the tuning- and deployment-process will be analyzed and reviewed. As a prerequisite, an initial process analysis is mandatory and beneficial for further considerations of the boundary conditions, pitfalls and bottlenecks. Based on the identified critical items further conclusions can be made in order to facilitate broad deployment scenarios of active sound-based features.

The task-based flow chart in Figure 4 shows the most important items of the actual work streams in order to develop the sound profiles. Here, three main sections resp. development phases can be identified which are time-wise distributed across a vehicle model development cycle. The flow chart might contain more subtasks - such

as measurement and documentation of results for example. However, these subtasks are consolidated to a single high-level item due to the limited amount of space in Figure 4. The three main sections will be discussed in the following:

1. target sound development phase/initial tuning phase, e.g. on prototype level '1+'
2. complexity-related deployment and verification phase, e.g. prototype level '2+'
3. sound profile release and software validation

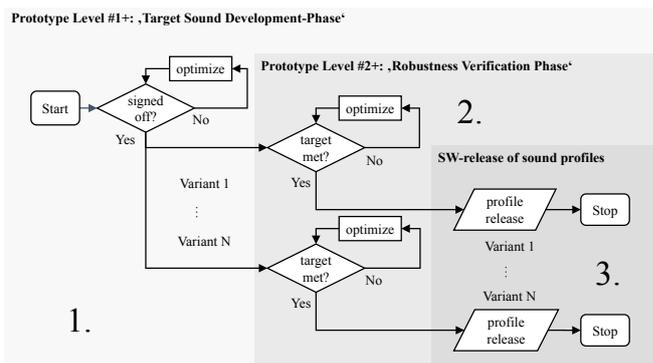


Figure 4: Task-based flow-diagram of the tuning process (condensed to the most important items, e.g. 'optimization').

Target Sound Development-Phase: The 'target sound development task' usually starts with an initial tuning phase - typically on an early prototype level with (mostly) representative vehicle body and interior trim design. This does happen on a limited amount of prototype vehicles and thus only a subset of the effectively required sound profiles can be created. The definition of the 'target sound' is an iterative process that can be quite elaborate due to experimentation on the vehicle which requires a significant amount of time resources on the test vehicles. Therefore, virtual methods can help to reduce test time significantly. However, tuning on the vehicle is still mandatory when it comes to the details. Furthermore, the amount of required iterations is directly linked to the NVH-sign-off process for a newly developed sound design resp. sound profile. It is questionable whether the tuning vehicles have a completely representative primary sound-behavior due to ongoing hardware and software development iterations that are related to the primary sound (base sound-related NVH-countermeasures). As a consequence, this might require additional re-tuning activities both for ANC- and ASD - which can become a very critical and elaborate task as soon as the second section of the flow chart is considered.

Complexity-related Deployment- and Verification-Phase: Once the new sound design was approved and sign-off was given, the second section of the flow chart starts. This is the most critical and challenging phase, since here it needs to be ensured that the sound design is deployed for all relevant variants (*Variant 1 ... Variant N*). Actually, the main objective is that all variants do have an identical NVH-performance

and sound character - as was defined initially as the target sound. As a pragmatic approach, it should be considered whether slight tolerances are allowed for each variant. However, the effort to deploy multiple sound profiles should not be underestimated: Here, many bottlenecks and pitfalls play an important role and can create serious obstacles. These can be for instance, the limited amount of time resources on the test vehicles. Therefore, the tuning itself needs to be effective and optimized using well-designed tuning tools and methods. Furthermore, vehicle resources can be critical. Possibly, only a subset of the vehicle variants can be verified in terms of corresponding sound profiles. Here, the most relevant variants need to be identified - based on a proper analysis on vehicle, system and component level.

As a consequence, it becomes clear that a high amount of tuning and verification work is required. Moreover, the deployment process is highly parallelized and fragmented in terms of test resources and timing. The example above was discussed on the basis of a sound design for a single powertrain variant. The discussed pitfalls become even more critical as soon as a higher amount of sound designs has to be deployed for a single vehicle line or even multiple vehicle lines in parallel.

Sound Profile-Release and SW-Validation: The third section of the flow chart depicts the release phase of the sound profiles as a part of the active-sound ECU-software. The SW-release usually does happen across the different development milestones and (subset of variants) should finally contain the fully matured and robust tuning parameters for vehicle mass production (superset of vehicle variants). Here, the proper function of the sound profiles and of the remaining HW- and SW-infrastructure needs to be ensured. Different strategies exist here, e.g. by downloading the sound profiles end-of-line at the production plant of the supplier or of the vehicle manufacturer.

Summary and Conclusion

Selected aspects with respect to the deployment of active sound-systems in the automotive industry were analyzed and discussed. The deployment is not trivial and does require a high amount of tuning and verification work to ensure a robust system performance. Moreover, the tuning and deployment process is highly parallelized and fragmented because of vehicle-line complexity. Here, it is crucial to identify the most important vehicle variants, features and corresponding acoustic and non-acoustic impact factors. Therefore, a deeper analysis and identification of these impact factors on vehicle, system and component level is required. In this context, the discussed problems demand for intelligent implementation processes, advanced and innovative engineering methods and well-designed tools in order to facilitate the deployment of active-sound features on a manageable level. All considerations within this article hold for other application scenarios as well, e.g. for active sound-applications on HEV- and BEV-vehicles. Finally, an enriched deployment process allows to concentrate on the actual task

- namely creating an excellent NVH-performance and sound quality that finally can be experienced on the vehicle without compromises.

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