Current Status and Future Development of ANC Systems

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Active noise control (ANC) has long been seen as emerging technology. During recent years, however, it became popular in new vehicle and infotainment platforms within a broad range of OEMs. This article summarizes the current status and lessons learned of production systems (as well as those entering production soon) and gives an outlook on how ANC and related technologies will integrate in future vehicles and audio/infotainment architectures.

The acoustic functionality required from and delivered by current production ANC systems is to cancel dominant engine noise orders of an internal combustion engine inside the vehicle cabin. Cancellation is required for all passenger seats, so it needs to act globally within a cabin.

Global cancellation requires taking the complete interior sound field into consideration. This is best done by a modal description of the vehicle interior sound field, the placement of speakers needed to control relevant acoustic modes, and placement of microphones to observe relevant acoustic modes. The effective cancellation frequency range is determined by the interior modal density of relevant noise components (depending on the interior space as well as wavelength/frequency) and the number and placement of microphones and speakers. These are all physical/acoustical limitations and do not depend on any specific algorithm or control software.[1]

Due to cost restrictions, the number of speakers and microphones as well as specific speaker capabilities at the lower frequency range are commonly limited. Today a typical production setup consists of four microphones and four to five speakers (door woofers plus subwoofer if available) that can work globally up to about 200 to 250 Hz (depending on vehicle interior and component placement), while the lower frequency limit is typically given by the speaker capabilities and might be in the 30 to 70 Hz range.

While a four-microphone setup is a typical in current production systems, some systems use fewer microphones, mainly due to cost restrictions, but sometimes also due to technical limitations (for example integration into existing audio system designs with a limited number of available pins within pre-defined connectors).

With a two microphone system, the first cabin cavity mode can be addressed, resulting in significant booming noise reduction below about 60 Hz. Adding a third microphone will typically allow for global cancellation up to 120-130 Hz and might give good results even for higher frequencies. But there is a high risk that global cancellation cannot be achieved for all frequencies and seating positions up to about 200 Hz. Note that this 200 Hz is often desired, because it is equivalent to the firing frequency of an I4 engine at 6000 RPM, and this firing frequency typically is the dominant engine booming noise component. So, if global cancellation up to about 200 Hz is desired, it is strongly recommended to use a four microphone setup.

One quantity that is frequently varied in ANC systems is the number of engine orders to be minimized within the working frequency range. A minimum requirement is cancellation of at least two engine orders, typically the firing frequency (or second engine order of an I4 engine) and its first harmonic (the fourth engine order of an I4 engine).

The functional range of production systems might be much higher, say up to eight engine orders, many of which might only be cancelled for some specific rpm/frequency range. Also, while the rpm ranges are fixed for traditional engines, newer engine concepts like cylinder deactivation (called AFM, COD, DOD, MDS or

likewise at different OEMs) ask for multiple setups with seamless transitions between engine operation modes. The impact of a higher number of engine orders to be cancelled includes:

- Increased computational requirements; i.e. MIPS and memory
- Higher tuning sensitivity due to the waterbed effect
- Higher tuning effort due to more complex tunings (e.g. multiple engine modes, more orders to refine)

Any of these effects is a good reason to keep the number of engine orders in production systems as low as possible even if a higher number is technically feasible.

Today's production systems are based on engine rpm and implemented through adaptive filtering, usually based on some kind of filtered-X LMS processing.[3] The standard system uses "feed-forward" control from RPM input to speaker output. Effectively, they are feedback control systems with the feedback loop going from the error microphone through the adaptation process to the speaker signal. The RPM input serves as an additional input only to control the feedback system response. It is crucial to be aware of this as all feedback systems bear the inherent danger of causing unwanted side effects due to stability issues.[2]

Today it is possible to analytically describe and calculate the control system sensitivity function of this closed control loop,[4] thus including all side-effects of a specific control settings due to Bode's sensitivity integral (waterbed effect). Due to these advanced modeling capabilities, the understanding of the system behavior down to the actual operational vehicle tuning has made significant progress recently.

Many of the key factors influencing the integrated system's sensitivity function depend on the vehicle, component and component integration side and thus are beyond the control of an ANC system or technology provider. Within the range of an ANC system, the key factor influencing ANC performance is the system latency. This is the signal latency added by the control system to the overall latency of the feedback loop in the working frequency range. Major contributions are given by:

- DC decoupling of microphone phantom supply voltage
- A/D and D/A converter delays due to internal latency (sigma-delta converters with integrated low-pass filtering)
- DSP processing latency, determined by sampling rate and block size.

There is no black-and-white separation margin for system latency; it is more a gray area with usable ANC performance decreasing/ANC side effects increasing gradually. Neglecting the ANC processing itself and assuming a 48 kHz audio sampling rate, an ANC system latency of 2 msec is fine, and 3 msec determines a typical upper limit for an acceptable latency. Beyond that, significant artefacts and/or system performance degradation are to be expected.

Uncertainty

The main issue to be taken into account with ANC systems is uncertainty. As outlined above, an ANC system is a feedback control system with the error microphones, the control unit, the speakers and the vehicle interior sound field contained in the feedback loop of the system.

With respect to robust control system design,[3] any uncertainty in these components needs to be covered and will have an impact on control system performance. Therefore, it is important to keep uncertainties and tolerances of system components as low as possible.

Major sources of uncertainty are:

- Vehicle interior production tolerances
- Passengers seated in the vehicle (number, placement)
- Vehicle openings (windows, doors, trunk door, sunroof)

- System component tolerances (microphones, speakers)
- Changes due to environmental conditions (temperature changes)

The higher the uncertainties, the more robust an ANC system needs to be set up and the less performance can be achieved, even under nominal conditions. Therefore, minimizing uncertainties is a major system design task. This might impact microphone positioning as well as selecting microphone or speaker materials to minimize temperature impact on component characteristics.

For example, current datasheets indicate that MEMS microphones show lower production tolerances and less temperature dependence of the micropone frequency response than ECM types. Therefore, MEMS is a promising technology for higher ANC system performance even if this performance increase cannot easily be stated quantitatively.

The Müller-BBM approach to manage uncertainty for ANC systems is to measure and model the different components of the overall uncertainty as much as possible. This does include a multitude of interior transfer function measurements during tuning with a different number of passengers seated and vehicle conditions altered (windows open or closed). Based on this data, ANC system parameters are determined during system tuning to guarantee robust stability of the system under these expected operating conditions.

Audio System Integration and System Hardware

To bring ANC into production vehicles, audio system integration is a key aspect. This is, as the vehicle audio amplifiers and speakers are typically to be used for audio and ANC in parallel, to save cost, weight and packaging space. Closely related is the question on how to supply vehicle data to the ANC system, i.e. rpm, but also other relevant information on vehicle operating conditions like cylinder activation states or door status.

A typical first-generation approach was to add an extra control unit, more or less an additional DSP audio amplifier. This approach results in the most simple integration as you just need to integrate the extra box into the wiring harness/speaker wiring. So, there is no impact on the existing audio system, allowing easy retrofitting of existing architectures.

Vehicle and engine data can be fed to this extra unit as required without taking into account existing infrastructure. Also, since you only need to drop in the extra box into vehicles with a need for ANC, this approach is very flexible for small ANC data rates. However, since you need to add a complete extra unit, it is relatively expensive per ANC vehicle. Nevertheless, you still find this approach even in current production vehicles due to the ease of integration, but it is becoming less popular for all-new designs.

A typical second-generation approach was to add some dedicated processing resources for ANC into some existing audio component. This could be some kind of plug-in module for a head unit as well as some dedicated DSP added to an existing audio amplifier design. This already requires significantly more integration work in terms of hardware and vehicle data integration. If necessary, some extra communication line needs to be added to manage excessive bus system/gateway latencies. So no extra control unit is added, and all of the associated infrastructure cost (including package and weight) are mitigated. This approach is still followed by new designs also in case DSP resources are not easily available elsewhere or latency requirements cannot easily be met with standard components.

What I would like to call a third-generation approach is fully integrating ANC software functionality within general system hardware components. Basically, there are two approaches:

- Software integration within powerful DSP hardware. This approach is followed in premium audio amplifiers with powerful DSP resources (some analog devices SHARC system). Today's ANC typically requires only a small fraction of the DSP core resources (say, 10% for some typical system). So ANC can be added as a software component on the amplifier without extra processing hardware if it is taken into account early at DSP resource management.
- Functional software integration in complex system-on-chip (SOC) solutions. A good example of this approach is the NXP Dirana 3 radio SOC. Among a fully featured set of radio and standard audio processing related functionality on a multitude of processing cores, this SOC also offers a freely programmable Cadence Tensilica HiFi 2 core, which is more than powerful enough for standard head-unit-related ANC functionality (four microphones, four to six speakers, half a dozen engine orders). As a result, no extra processing silicon is required in a standard radio head unit. Other powerful SOCs are currently following this route to integrate freely programmable DSP cores that are well suited for ANC purposes and allow for this very tight and cost-effective integration.

System Production Tuning

One core issue impacting the broad application of ANC is neither directly related to the ANC technology itself nor to the in-vehicle integration of an ANC system – system tuning. As described above, an ANC system requires tuning. This contains the determination of a suitable set of vehicle interior transfer functions (typically called "secondary transfer path" in the ANC literature) and of some algorithm parameters, so as to determine engine orders and RPM ranges to be controlled but also algorithm specific parameters.

The key issue is the vast number of different tunings. They depend on the vehicle audio system/interior transfer characteristics as well as the vehicle powertrain as the relevant noise source, so they need to be specific per:

- Vehicle body style (and in a worst case interior variant)
- Audio system level (defining amplifier and speaker capabilities)
- Vehicle powertrains.

For example, for a vehicle program with three body styles, four audio system levels and three powertrains, you will end up with a total of 36 different tuning datasets.

To generate and validate them, each of the vehicle variants would be required for tuning, but sometimes all variants are not even being built as prototypes. So in addition to tuning time and related human resources, vehicle availability is a key factor and a driving force for more virtual tuning processes, including data reuse and detailed tuning process management. Advanced modelling and calculation concepts described above turn out to be very helpful for this purpose.

At this time, with experienced tuning engineers, tuning very complex ANC setups (including five to ten engine orders and cylinder deactivation modes) including tuning validation on a test track and documentation measurements requires less than one week of vehicle availability per variant. While still under development and validation, the advanced modelling concepts will soon enable not only reducing the required time a vehicle needa to be available for measurement, tuning and validation further by at least another 50%, but it will also allow the purely virtual tuning of variants and reduce the number of prototype cars required.

Perspectives of In-Vehicle Infotainment (IVI)

Thirty years ago, vehicles were equipped with radios to play music and give traffic information. Radios, additional amplifiers and speakers were hot aftermarket items; the number of speakers was low, as was the sound quality. All of this has drastically changed.

Today, it is not about radio any more. The system has evolved to what is typically called in-vehicle infotainment. Cassette players as additional (analog) audio sources are a technology of the past, as are digital CD players. USB for mass data storage sometimes is still available, but the key about "connectivity" are different wireless, "over-the-air" interfaces: Bluetooth and WiFi within the vehicle and GSM/UMTS/LTE for mobile services.

All systems have moved to digital, with digital signals converted to analog physical signals for human perception – on different optical displays (cockpit, head-up, center stack, rear-seat entertainment, etc.) as well as power amplifiers and speakers for audio.

If all this sounds like some computer topic, not like an audio device and even less like some NVH system – then this assessment is absolutely correct. Future IVI systems will be a kind of "center-stack computers" to deal with any kind of media content, a networked communication hub to serve about a dozen different digital bus systems and independent media streams, probably on a per-seat/per display basis. As the content and interfacing sources

are mainly coming from the consumer electronics side, changes are very fast, and technology generations are measured in months, not years. So, there is a permanent need for flexibility and updates.

This has led to a significant paradigm shift in IVI: a center-stack computer really is understood to be a highly efficient, very powerful mobile general-purpose computer, like the consumer electronics hardware, to run typical consumer electronics operating systems (Android, iOS, Windows, Tizen or some other kind of Linux). The rationale is that this might more easily allow keeping pace with consumer electronics development and offering all the complex software and evolving protocols, connectivity and media content more or less "for free." Current and upcoming silicon clearly shows this direction.

One interesting aspect here is that the role of audio/IVI Tier 1 suppliers changes significantly. The silicon providers move forward more and more to supply basic software (including OS and specific "eco-systems") for their silicon, and this software gets more and more open and Tier 1 independent. OEMs focus on user experience (UX) – the extension of what was once the user interface – to create their own, distinctive customer experience. Tier 1s are somewhere in the middle, more reduced to system integrators and manufacturers. This will allow OEMs to choose software and functionality more easily, independent of Tier 1 and branding decisions.

From an audio perspective, there once was a good reason to go with amplifiers separated from the radio. Besides EMC, the main reason was packaging, which was mainly due to thermal loads associated with power handling. So we had large components, but we had even larger heat sinks.

As always when classical physics enters into the digital domain, things do not develop according to Moore's law any more. However, we have seen great progress in audio power handling, especially with the broad availability of highly efficient Class D amplifiers. Roughly speaking, thermal loads and power management is manageable for up to four standard speaker channels within a head unit/center stack computer (but probably still not easily for six). So, for standard vehicles, a highly integrated center stack computer based on some consumer electronics related operating system (and SOC) is the typical approach to be seen in upcoming years.

For more premium audio systems, those requiring more than six speakers, there still will be some kind of power/thermal issue with this very high level of integration, so detached power amplifiers will survive. They are very likely to be connected by some digital bus system like *most* (probably fading out), Ethernet (fading in) and dedicated specialized solutions like A2B. How much processing will be done in the detached units is still not decided and will differ by OEM and audio architecture.

ANC and Future IVI Systems

How will the future of IVI systems impact ANC and the NVH community? From the view of strategic IVI planning, ANC is just one computational block that should be placed somewhere in the huge signal flow managed by the vehicle operating system. Unfortunately, this is a bit short sighted and will not work in practice. The key point is latency. Since ANC is a closed loop control technology, latency is of utmost importance. The latency is within the control loop, ANC processing and speaker output loop. It should be in the 2-3 msec range for good performance.

The key issue with any operating system is latency, jitter and real-time processing/overhead. To mitigate these effects and achieve stable and efficient processing, typical audio stream block sizes are 128 bits, 192 bits or even larger; resulting in 2.6 to 4 msec block duration at a 48 kHz sampling rate. Assuming three block durations for efficient ANC processing, this will result in 8 to 12 msec minimum latency just due to the digital signal handling by the operating system. This is not acceptable for ANC performance. As a result, ANC cannot be easily integrated into mainstream OS-based audio processing. Instead, some low-latency audio processing environment is required for ANC.

So, what will future system integration look like? Software programs offering a low-latency path are unlikely for the main processing cores even though they are a viable solution for dedi-

cated DSPs. Therefore, dedicated low-latency hardware needs to be added. This could be on-chip. Adding an additional low-latency core to a complex SOC such as Renesas R-Car or Intel Atom based designs very much like the HiFi core on the NXP Dirana. Or it could be by adding some small, dedicated low-latency DSP core to a system design, perhaps including additional peripherals like the Cirrus Logic CS470xx SOC.

While this may work nicely for systems with only head units, the situation with dedicated amplifiers will probably be different. Mixing of ANC and audio data needs to happen within the extra amplifier to avoid processing latencies. The computation of the ANC signals will then depend on the additional communication latency from head unit to amplifier. Bandwidth is probably not an issue here, but again it is communication latency. For example, there are central processor designs that need to run communication through the OS, so even if upcoming communication chips and protocols are fast, there is again a latency bottleneck. So, a careful system design is required, or alternatively, the ANC processing and low latency microphone signal routing needs to be done at the amplifier as it is done today.

Challenges of ANC in 2020

Thinking about challenges for ANC in the year 2020, the most predominant seems to be tuning. With the broader use of ANC technology, the number of tuning variants will significantly increase, and advanced tools with virtual tuning capabilities will be required to keep the tuning effort manageable. ANC probably needs to be taken into account at the strategic prototype vehicle planning to ensure that all required variants will be available.

Closely connected to the number of tunings is the question of how to get tuning data into production vehicles. To allow for the required flexibility and large number of different tunings, the only viable long-term perspective is at the end of the vehicle production line.

How will the customer acceptance of ANC develop? Will customers expect some generic engine sound related to a powertrain, or do they accept that the same powertrain might sound different depending on the audio system? Do customers even want to modify vehicle sound/ANC settings by themselves?

While this sounds philosophical, it is a major product strategy decision of an OEM. Do we want to control the subjective customer experience? If we sell positive emotions on the vehicle and powertrain via the vehicle sound, how well do we need to control this sound? Loosening this control will have multiple impacts. New business models may involve different audio levels within one vehicle to produce the same ANC performance.

A big challenge will also be to drive down the cost of ANC systems. Main cost drivers for ANC are added hardware components, especially microphones. From a technical perspective, MEMS microphones delivering sound pressure levels directly to suitable in-vehicle bus systems like A2B are feasible and might offer a way to reduce system cost and possibly result in even better performance data.

Commercial aspects will also be decisive for future technical ANC developments. Within demo cars, the feasibility of engine-order-based ANC for up to 600-700 Hz has been successfully demonstrated. However, a significantly higher number of microphones and speakers will be required for more local control. Whether this would be commercially viable is not yet clear.

The situation is similar for road noise control. This technology was successfully demonstrated more than 20 years ago.[5] Nevertheless, there are still significant technical aspects to be solved for a robust, production-ready system including integration with the audio system and the vehicle itself. It is well known that RNC performance will be quite limited due to the cost of multiple accelerometers mounted within the vehicle chassis. The high computational effort and audio system integration requirements for extremely low latencies will be significant.

On the other side, some technology that we clearly see integrated and merged with ANC is any kind of active sound design, probably including significant broader feature sets of today. Extra BOM cost for production vehicles will be negligible, so the technology will

surely be widely applied to enhance subjective vehicle ratings. However, active sound design is even more critical in terms of tuning effort and tuning processes. Also the application of this technology will depend on highly efficient tuning and sound design tools.

Conclusions

ANC today is a well-understood functionality and not black magic. It has been successfully applied to a broad range of production vehicles and will see a significantly broadened application in coming years. ANC functionality is available as generic software functionality on a broad range of processors and thus can easily be integrated into a variety of audio systems with different integration approaches.

What remains important with ANC is system and integration related topics primarily in three areas:

- Acoustic vehicle integration, including vehicle and component properties.
- Electronic system integration into the audio/IVI ecosystem, given the strict latency requirements for ANC.
- Management of vehicle variants, tuning variants and vehicle tuning.

These issues will be of major importance for future ANC system costs as well as performance.

References

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