

Current Status and Future Developments of ANC Systems

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ABSTRACT

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 paper 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.

CITATION: Schirmacher, R., "Current Status and Future Developments of ANC Systems," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2223.

CURRENT STATE-OF-THE-ART OF PRODUCTION ANC SYSTEMS

Acoustical Functionality and System Requirements

The acoustic functionality required from and delivered by current production ANC systems is to cancel dominant engine 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 in consideration. This is best done by a modal description of the vehicle interior sound field, effectively stating that control system speakers need to be placed to control relevant acoustic modes, control system microphones need to be placed to observe relevant acoustic modes and that at any frequency at best as many modal components can be controlled as the dimension of the control system (i.e. the minimum of the number of linear independent microphones/speakers/control system channels) is at that frequency. So 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 (e.g. [1], Chapter 10).

Due to cost restrictions, the numbers of speakers and microphones as well as specific speaker capabilities at the lower frequency range are commonly limited. Today a typical production set-up consists of 4 microphones and 4-5 speakers (door woofers plus subwoofer if available) which can work globally up to about 200 Hz 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 Hz (including sub-woofer) to 70 Hz (no subwoofer, limited door speakers only) range.

While a four microphone set-up is a typical current (and upcoming) production system, some production systems use a lower number of microphones, mainly due to cost restrictions, but sometimes also caused by technical limitations (for example integration into existing audio system designs with e.g. limited number of available pins within pre-defined connectors). With a two microphone system, typically the first cabin cavity mode can be tackled, resulting in significant booming noise reduction below approx. 60 Hz. Adding a third microphone will typically allow for global cancellation up to about 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 4 mic set-up.

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 2 engine orders, typically the firing frequency (i.e. 2nd engine order of an I4 engine) and its first harmonic (i.e. 4th engine order of an I4 engine). The functional range of production systems however might be much higher, say up to 8 engine orders, many of which might only be cancelled for some specific rpm/frequency range. Also, while the set and 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 is multiple, including

- Increased computational requirements, i.e. MIPS (often less critical) and memory (might be relevant e.g. for tuning dataset download times)
- Higher tuning sensitivity due to the wider bandwidth (see below)



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- Higher tuning effort due to more complex tunings (e.g. multiple engine modes, more orders to refine; in general: more parameters to choose and validate).

Any of these effects gives a good reason to keep the number of engine orders in production systems as low as possible (i.e. as required by NVH/giving significant customer benefits), even if a higher number is technically feasible.

Today's production systems are based on engine rpm (more general: noise signal frequency) information and implemented through some way of adaptive filtering, usually based on some (modified) kind of filtered-X LMS processing [3]. While the standard description is as a "feedforward" control system from some RPM input to the speaker output, effectively, they are feedback control systems with the feedback loop going from the error mic through the adaptation process to the speaker signal and the rpm input is serving as an additional input only to control the feedback system response. It is crucial to be aware of this as all sort of feedback system bear the inherent danger of causing unwanted side effects, e.g. due to stability issues (c.f.[2] for an overview on ANC system designs).

Nowadays, it is possible to analytically describe and calculate the control system sensitivity function of this closed control loop (e.g. [4]), thus including all side-effects of a specific control settings as e.g. due to Bode's sensitivity integral (waterbed effect). Due to these advanced modelling 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 line 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 ms is fine and 3 ms determine a typical upper limit for an acceptable latency. Beyond that, significant artefacts and/or system performance degradation are to be expected.

Uncertainty

A 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 need to be covered and will have an impact on the 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 (e.g. windows, doors, trunk door, sunroof)
- System component tolerances (microphones, speakers)
- Changes due to environmental conditions, e.g. temperature changes

The higher the uncertainties, the more robust an ANC system need 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 the selection of microphone or speaker materials, e.g. 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 mic 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 in general).

The Müller-BBM approach to manage uncertainty for ANC systems is to measure and model the different components of the overall uncertainty as good as possible. This does e.g. include a multitude of interior transfer function measurements during tuning with a different number of passengers seated and vehicle conditions altered (e.g. windows open/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

In order 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 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, as you only need to drop in the extra box into vehicles with a need for ANC, this approach is very flexible for small ANC retrofits. However, as you need to add a control unit, it is relatively