Practical aspects of implementing car interior active noise control systems

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When implementing real-world, close-to-production active noise control (ANC) systems for car interiors, many aspects far beyond textbook theory have to be taken into consideration – many of which might also be left out for first demonstrator systems.
Due to the predominant role of robustness and reliability, any kind of uncertainty in the system has to be considered carefully. Among others, the uncertainties and changes of the acoustical environment, e.g. due to temperature changes, number of passengers, open windows and also of system components, e.g. loudspeakers and microphones have to be measured and/or modeled. This also gives some new insight into the acoustical environment inside cars at low frequencies.
In addition, the quality of input data (e.g., the update rate for rpm information) is of major importance for the acoustical performance in terms of noise reduction.
Finally, stability analyses and robustness calculations must be extended to incorporate uncertainties as well as time domain effects even for more or less frequency domain problems like engine noise. This requires to re-formulate feed-forward systems as feed-back systems and calculate system responses.
Measurement results on the interior acoustics (and its uncertainty) as well as additional developments on ANC system robustness are presented.

1 Introduction

The reduction of car interior engine noise is considered to be one of the classical applications of active noise control (ANC). First experimental demonstrators are available for more than 15 years. But if the technology is considered for application in series production cars, there are a lot of additional requirements to be fulfilled, which might be left out at first demonstrators. Among them are, for example, stability and robustness with changing acoustical environments (temperature, occupancy) or the quality and availablity of engine data. This paper will present some of the issues envolved including typical values measured at real cars and demonstrates todays technological capabilites for this ANC application.

2 Description of the system setup

In this paper, we will consider an ANC system for the reduction of order-based engine noise in the vehicle interior. We will follow a feed-forward approach, which is based on a filtered-X-LMS scheme and implemented in a mixed time-frequency-domain approach. A typical system configuration consists of 4–5 loudspeakers and up to 6 microphones. Typically, 4–5 engine orders in a working frequency range of 30 – 250 Hz are reduced with such a system.

The filtered-X approach requires an estimate of the secondary transfer functions. The actual secondary transfer functions at system run time and the estimated ones (respectively the estimation error) govern important algorithm properties like stability, convergence speed and closed-loop gain of the controller. The classical stability criterium for single channel filtered-X is a maximum of the phase error of 90° of the estimate. This criterium can be extended to multichannel systems and will lead to matrix expressions beyond the scope of this paper.

3 Acoustical transfer functions

In the frequency range below approx. 300 Hz, the interior sound field of a passenger car can be reasonably well described by normal modes. Applying a modal analysis to the interior airborne sound field leads to the following main properties:

- The interior volume is highly damped, the modal damping is typically in between 2 and 5 %, but can be much higher for some modes.
- The number of modes increases proportional with frequency f and not f^3 (as to be expected for a voulume with rigid walls).
- Some modes show strong fluid-structure-interaction (FSI) with the body and mounted interiors.
- Opening windows and that like results in an additional Helmholtz resonance and a shift in the eigenfrequencies and mode shapes (sound pressure distributions).
- The modes change differently with changes of the acoustical environment, depending e.g. on the strength of the FSI.

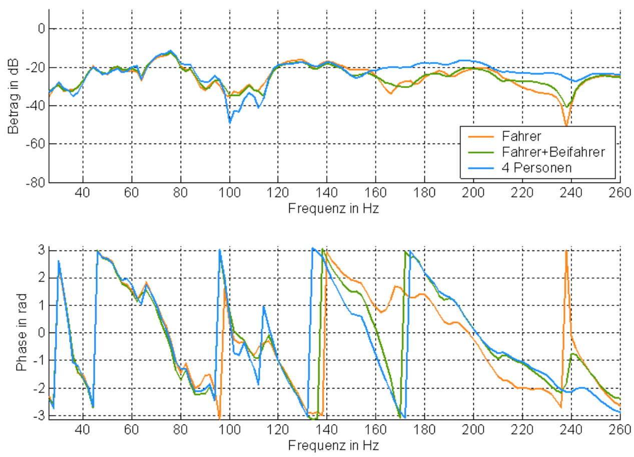

Figure 1: Transfer function from a door-mounted loudspeaker to a headliner-mounted microphone depending on the occupancy of the interior

Figure 1 shows as an example the dependency of the transfer function in between a door-mounted speaker and a headliner-mounted microphone in dependency of the occupation in a typical passenger car. The scatter band for openings is in the same order of magnitude.

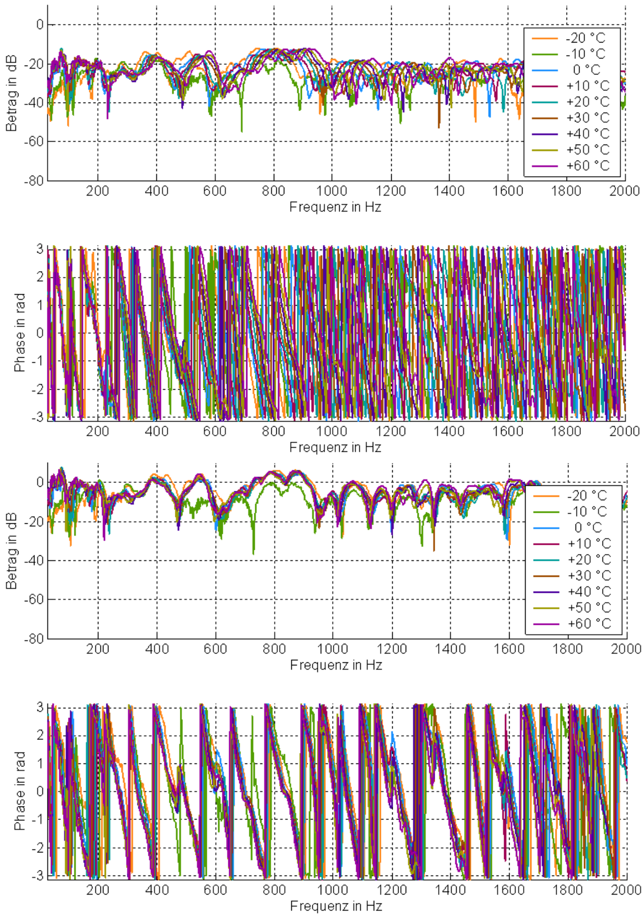

Figure 2: Transfer function from a door-mounted loudspeaker to a headliner-mounted microphone depending on the temperature of the car, top: unscaled raw data, bottom: re-scaled to 20°C

Another relevant quantity to describe the acoustical environment is the temperature of the car. Figure 2 shows as an example the transfer function for a temperature range of -20 to +60°C. The raw measurement data give a quite confusing picture (top) that can be cleared to a great deal with a scaling proportional to $\sqrt{T}$ to reflect the changes of the wavenumber according to temperature. However, at low frequencies, this simple model does not fit well.

4 Control loop gain

When applying an ANC system, the overall acoustical influence of the system is very important next to the level reduction at the engine orders. There must not be any audible degradation of audio signal or human speech or any other kind of sound artefacts. Nevertheless, they might occur (at least under some operating conditions) if the algorithms and parameters are not well choosen.

Typically, an ANC system is analysed as an adaptive feed-forward control system with some reference signal to be fed through some (adaptive) filter to the control output. Neglecting adaptation, this results in an LTI system and so no acoustical artefacts at non-working frequencies. To determine the complete system behaviour, it is very useful to analyse the system in an alternative way: as a feedback control system from error microphone to speaker output, additionally controlled by the engine rpm. This way of modelling allows the determination of the closed loop gain of the control system for every parameter set (rpm, engine orders to be reduced, etc.) for all frequencies and thus including all acoustical influences and artefacts of the system.

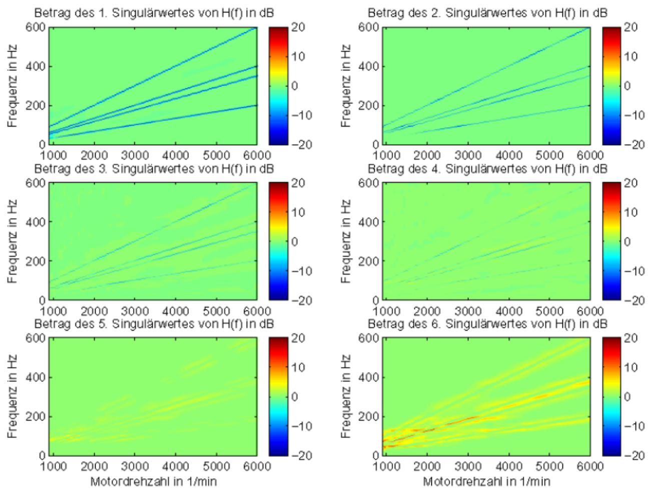

Figure 3: Singular values of the closed loop transfer function matrix for a badly parameterised ANC system showing acoustical artefacts.

Figure 3 shows the results of such an investigation: It displays the 6 singular values of a badly parameterized ANC system with 4 speakers and 6 microphones. The system is set up to reduce 2., 3,5., 4. and 6. engine order noise. The cancellation is clearly visable at the small singular values. The large singular values on the other side show significant detrimental increases of the sound field inside the car at some fixed frequencies and *in between* the narrowly spaced engine orders. This effect shown here by analytical computations based on control theory can easily be reproduced in real systems in cars and is often considered to be some "instability". In fact it is the "waterbed effect" of the control system, which is perfectly stabel under this conditions.

5 Engine data

A further important issue for implementing an ANC system in a car is the acquisition of the engine rpm. The traditional approach is to use an analog pulse signal allowing a strict synchronisation of the ANC system and the engine. This approach is no longer appropriate in modern cars with digital bus systems for information exchange. In these cars, CAN bus systems (asynchron, serial busses without guaranteed response times) are the current standard for engine data distribution inside the car. This results in new challenges for ANC systems.

In addition, the update rate of rpm information can be rather low on these busses. While it is typically about 10 ms on powertrain CAN busses close to the engine compartment, at typical audio system locations as trunk walls you will only find some slow body CAN with about 100 ms update rate and some intermediate delays by gateways,etc.

In such environments, appropriate measures must be taken by the ANC system to give good noise reductions with low data rates and delays. Figure 4 shows that such solutions are available.

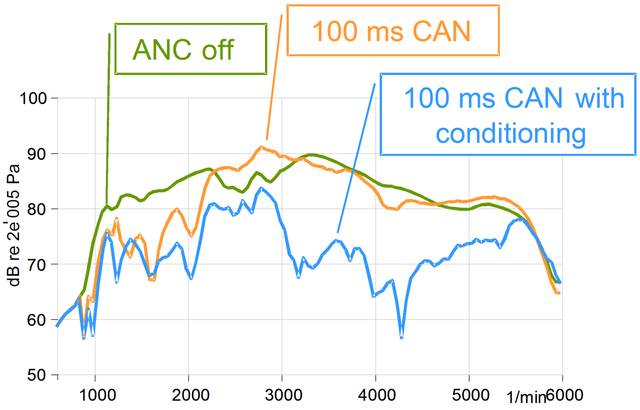

Figure 4: Order level of the 2nd engine order, measured at an interior microphone. ANC off, ANC with rpm via CAN and 100 ms update rate directly and with appropriate conditioning.

Conclusion

Actual ANC sytstem technology allows to master the issues discussed in this paper. The scatter band of secondary transfer functions can be measured and (at least partially) modelled. This allows the design and parameterisation of control algorithms that are robust for these anticipated uncertainties. The good news is that this does typically not lead to significant decreases in performance of the systems. Only extreme changes as opening doors or the trunk result in changes that require switching the system.

Looking on electro-acoustic components like microphones or speakers, it can be seen that by now specifications are lacking relevant properties (e.g. transfer function changes over temperature). Nevertheless, components with required properties and reasonable tolerances are available on the marked, even in a typical automotive price and quality range. Adding and clarifying specifications and proofing these properties remains a major task.

The complete function and the acoustical influence of the systems is understood very well. Based on analytical calculations and simulations it is possible to choose algorithms and parameters in a way that acoustical artefacts can be reliably excluded while at the same time performance can be maintained.

Automotive interfaces like low speed CAN busses which are required for integration in production vehicles give results that are well comparable to traditional synchron pulse interfaces.

By research and development work throughout the last years, a broader series application of ANC system has been well prepared.