Silence is golden

Active exhaust silencers in vehicles

Noise pollution impairs the quality of life just as much as any other form of pollution, but noise cannot always be avoided. So even as far back as the 1930s, researchers began looking for ways to cancel it out with antinoise. The algorithms for active exhaust mufflers are known, and their advantages are clear, but to date it is not possible to produce electronic silencers for vehicles, except under ideal conditions. The challenge is to get these silencers out of the laboratory and onto the road.

Advantages of Active Noise Control

- More efficient reduction of dominant engine orders, so silencers are smaller
- Lower exhaust backpressure, resulting in higher engine performance and in some cases lower fuel consumption
- Customizable vehicle sound
- Versatile silencer design, meaning more reusable components
- Simplified development processes and shorter development times

The purpose of an exhaust system is not only to lead combustion exhaust gases away from the vehicle safely, but to reduce noise emissions also, i.e., to muffle the sounds caused by the combustion process.

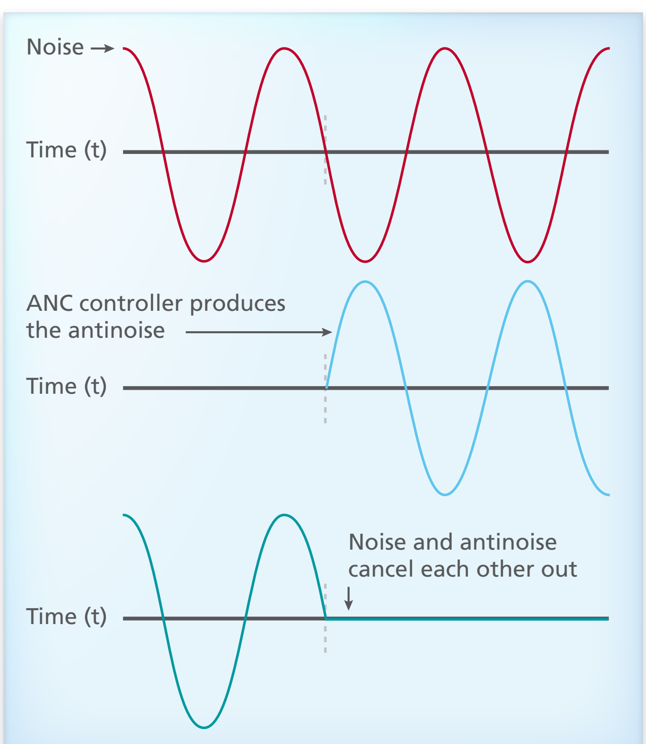

Figure 1: Active silencing by antinoise.

The ActiveSilence® system from Eberspächer goes further; not only muffling noise better than anything before it, but also modifying the entire sound profile of the vehicle.

The Basic Idea

Using the principle of destructive interference, a sound source generates a sound with the same amplitude and frequency as the unwanted sound. When the two sounds are overlaid with a phase shift of precisely 180°, they cancel each other out. This principle also plays an important role in active noise control (ANC) for exhaust systems. The control works perfectly under idealized laboratory conditions, but getting it onto the road is a major challenge. The ANC system's components such as the loudspeaker are very sensitive, and the exhaust system's ambient conditions make it difficult to achieve an optimal system. The loudspeaker and the microphone have to withstand exhaust temperatures that range from -30 °C during a cold start to +700 °C during peak performance, plus moisture, shocks and vibrations. The control also has to handle rapidly changing parameters such as engine speed and sound pressure level.

The Control Design

The primary sound components in an engine's exhaust system are the harmonics of the ignition's frequency, meaning that combustion engines can be classified as narrow-band sound sources. Our studies show that the most practical approach to active noise control in this case is an adaptive narrow-band feedforward control. The reference signal with information on the state of the combustion engine (speed, load) comes from the engine ECU via the CAN bus (figure 2). The ANC controller uses the information to control the loudspeaker with a 180° phase shift (feedforward part) and generate the secondary noise to cancel out the engine noise. The microphone picks up the residual noise, which the ANC then minimizes.

The control requirements are tough:

- Maximum efficiency over the greatest possible frequency range to suppress a broad noise spectrum
- Flexibility with regard to installation so that the system can be used for various engine families from different manufacturers
- Adaptivity to varying physical parameters such as temperature, vibrations, and shocks
- High robustness and reliability in all system elements
- Simple control electronics

The ANC controller generates the secondary noise via a secondary sound path. The transfer function between the controller output (control

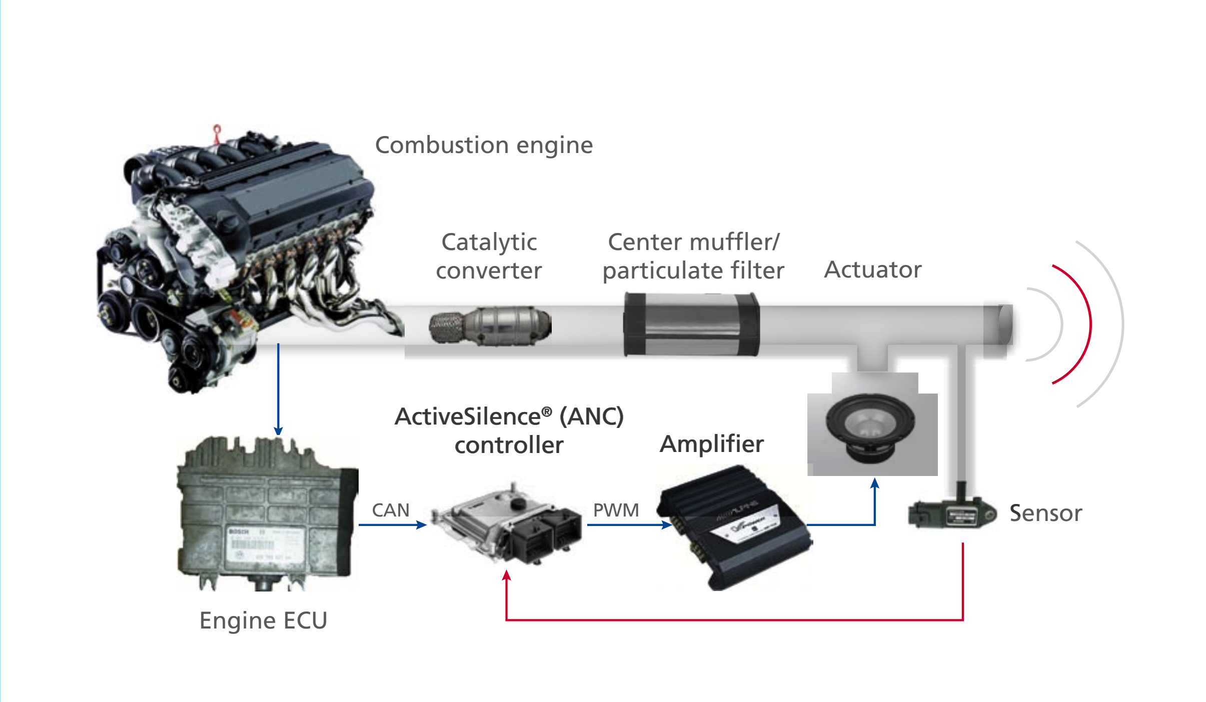

Figure 2: The control design.

> "The MicroAutoBox enabled us to develop a cost-efficient, integrated solution and to further optimize the overall system."
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signal) and its error signal input (error microphone signal) is called the transfer function of the secondary sound path (figure 3).

The ANC controller

- Reduces dominant engine orders in a frequency range of 35-400 Hz
- Increases frequencies selectively to achieve a target sound
- Identifies the transfer function of the secondary sound path even with engine noise

Model-Based Development Process

In the model-based development process, various simulations showed that the control returned the correct results.
The first step toward practical application is to implement the ANC algorithm on a dSPACE MicroAutoBox used as a prototyping system. To do this, we simulate the engine noises by replaying recorded exhaust noises via a loudspeaker in the laboratory. This lets us check whether the controller functions correctly on the MicroAutoBox. With dSPACE ControlDesk, we can adjust and optimize parameters such as the necessary filter length of the embedded controller. At this point, the MicroAutoBox is ready for use in the demo vehicle. The ANC controller is given further reference data such as engine speed, engine load, and vehicle speed via the vehicle powertrain CAN. Using the results of previous analyses, we study the properties of the overall system and optimize its total performance. The dynamic behavior of the system, particularly its effect on the criteria for the transmission function, is investigated in detail. The MicroAutoBox allows us to develop and refine an inexpensive and integrated solution.

The Test Vehicle Setup

We installed the ANC system in exhaust systems for a 4-cylinder gasoline engine. The direct injection system is fitted with a dual exhaust

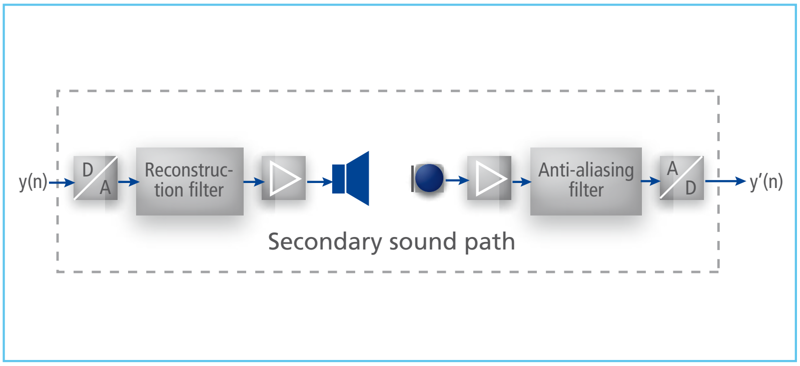

Figure 3: Transfer function between controller output and error signal input.

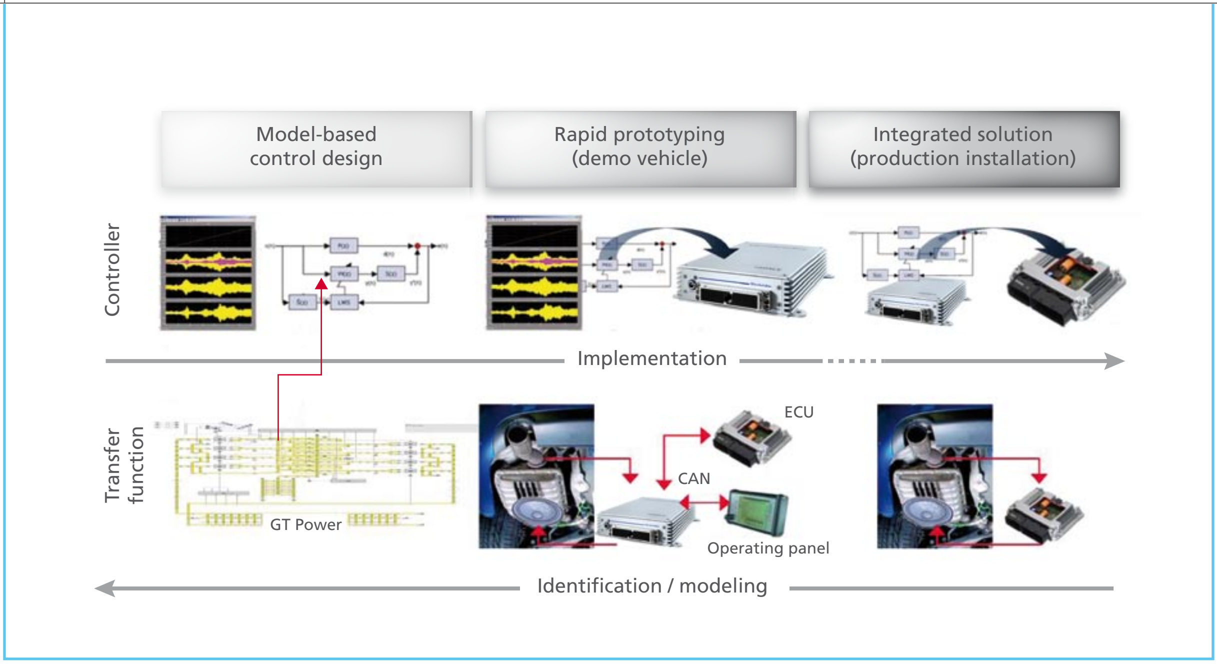

Figure 4: The development process – from model-based development to integratable control.

system as standard, so two active silencers were used to replace the conventional rear-exhaust silencer. The active silencer contains a microphone and loudspeakers that were specially developed to withstand the high temperatures and provide high output performance. All the other exhaust system elements, such as the catalyst, remained as they were. The exhaust system needs other electronic components in addition to the conventional silencer system. We used the following in this project:

- A dSPACE MicroAutoBox for real-time algorithm processing
- An amplifier to control the "canceling" antinoise loudspeaker with around 40 W maximum power
- An operating console in the driver's cab for setting predefined sound profiles and monitoring system status
- A microphone amplifier to return residual noise to the controller

Results

With more than 50,000 kilometers driven within 18 months, we were able to install and test the ANC system in various vehicles. We found a considerable reduction in exhaust noise in every case. Moreover, not only can the noise be reduced, the sound can also be improved. This means that the ANC system can be adapted to the vehicle, the driving situation, and the driver's wishes. The ANC system's acoustic performance was tested on a chassis roll test bench at full acceleration, with wide-open throttle (WOT) in third gear. We adjusted the controller so that it reduces the dominant engine orders 2, 4 and 6. The exhaust noise was measured at a distance of 0.5 m and at an angle of 45° to the exhaust tailpipe.

When the ANC system is switched off, the sound level is around 5 dB(A) higher than with the standard production system, because the original

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In 1999 he completed his doctoral thesis on active silencers. He has been responsible for developing exhaust system acoustics at Eberspächer since 2000.

About Eberspächer

Founded	1865
Headquarters	Esslingen am Neckar
Employees	5,575
Turnover	€ 2,239.9 m (2008)
Products	Exhaust technology: catalytic converters, soot filters, silencers Auxiliary heating systems for cars, transporters, trucks, buses, construction machines and boats

passive silencer is no longer present. With the ANC system switched on, however, we measured a significant reduction of 2 to 8 dB(A) compared with the production system. We therefore achieved an improvement in noise levels over almost the entire engine speed range. The same measurements were performed for the 2nd engine order. The positive effect of the ANC system was clear here. Reduction started at an engine speed of 1200 revolutions per minute (40 Hz), and the noise was reduced by 10 to 20 dB over a wide range.

The noise level was also considerably reduced with other engine orders, so the exhaust noise had practically no additional effect on the noise level in the vehicle interior. We demonstrated that – especially in our demo vehicle – it is possible to achieve a degree of acoustic comfort that is otherwise present only in luxury vehicles.

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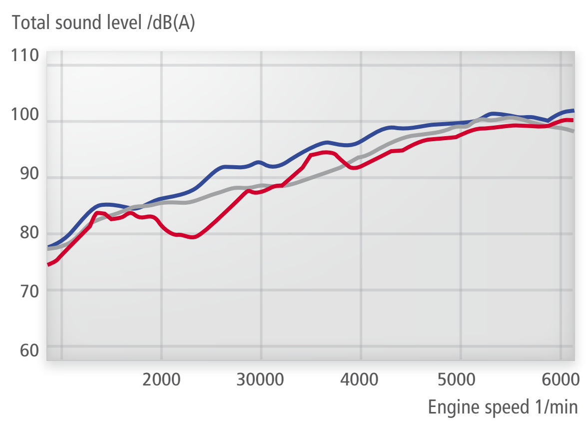

Figure 5: Overall sound level for a 4-cylinder gasoline engine (gray = standard production system, blue = ANC system switched off, red = ANC system switched on).

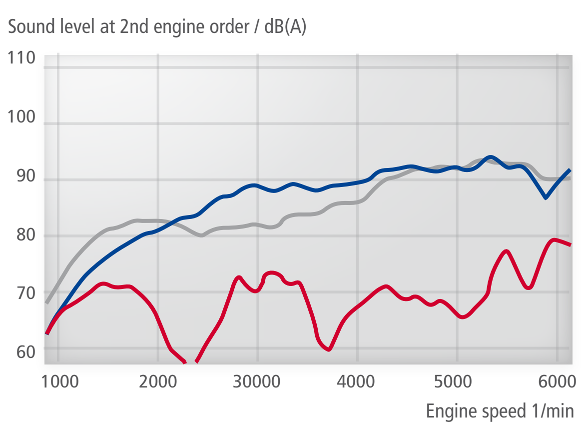

Figure 6: Sound level of the 2nd engine order for a 4-cylinder gasoline engine (gray = standard production system, blue = ANC system switched off, red = ANC system switched on).

Summary

We successfully took the ANC system out of the laboratory and put it on the road as the ActiveSilence® system. It performed beyond our expectations, even under adverse conditions. We verified all its functional benefits, such as reducing the noise, the volume of the silencers, and the exhaust backpressure. Our next step will be to reduce system costs. The system will be put in production vehicles only if the additional costs for loudspeakers and controller hardware and software can be offset either by greater functionality or by some other added value for the customer.

Glossary

Sound – Gas pressure fluctuations that consist of a basic frequency changing over time and its harmonics. The harmonics determine the characteristic acoustic impression of a sound.

Engine orders – An engine order states a frequency (harmonic) in an engine's frequency range that is a multiple of the engine speed. For example, the 2nd engine order is the harmonic that corresponds to twice the engine speed.