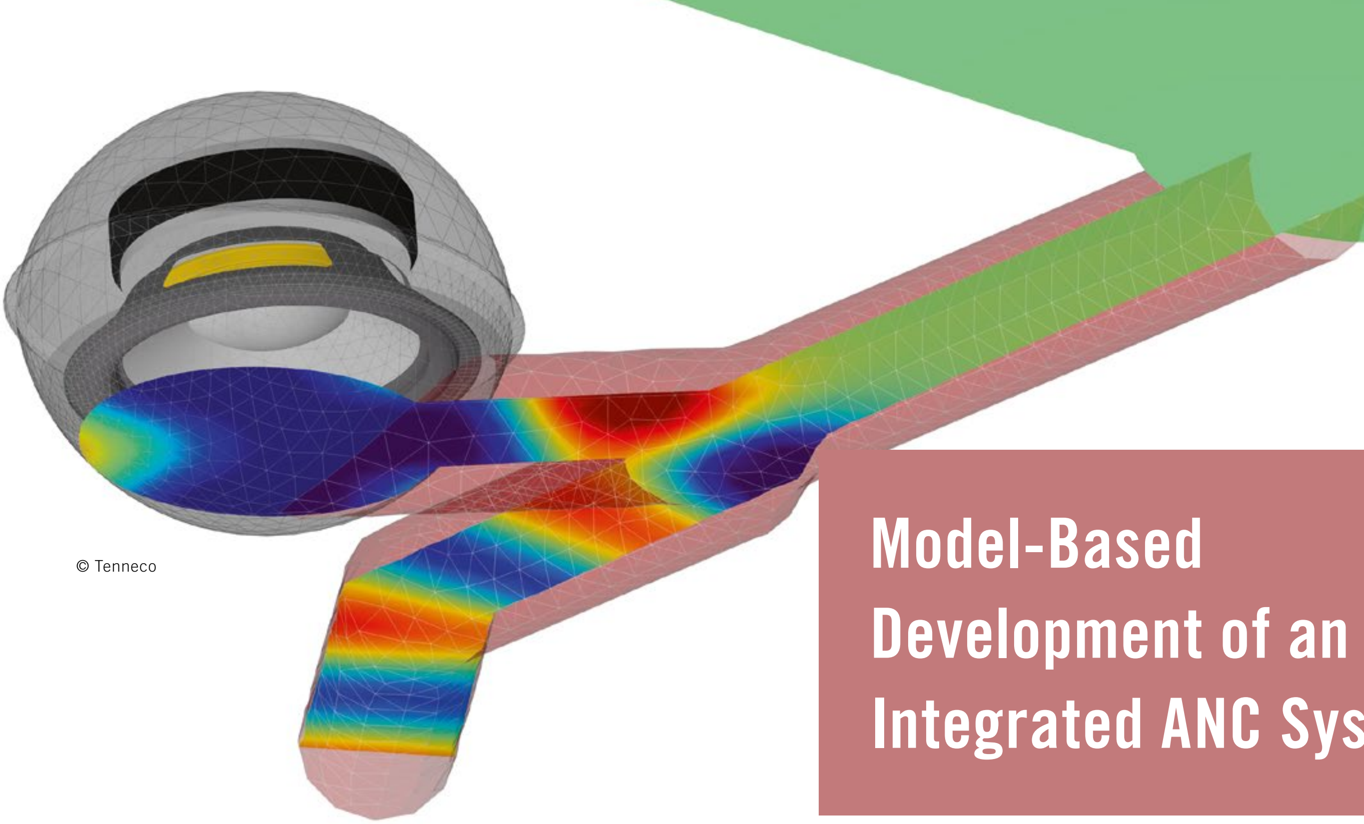


© Tenneco

Model-Based Development of an Integrated ANC System

Technologies using active components to reduce engine noise in the exhaust will, without much doubt, expand widely in medium term. Model-based approaches are necessary to deepen the system knowledge, which consequently minimises the development time. In this article, two modelling approaches are presented and shown as complementary tools to each other.

MOTIVATION

Particularly at low engine speeds, the engine orders appear as a dominant booming compared to the exhaust flow noise, especially when the engine is running down. Active Noise Control (ANC) is a potential alternative for achieving noise reduction of the dominant engine orders emerging in the exhaust system. It is based on the superposition principle of sound waves. In this way, the sound pressure level (SPL) of the dominant engine orders in the tailpipe can be reduced by up to 25 dB. ANC systems increase the constructors' possibilities, not only saving constructed space and weight but also allowing flexible packaging of the noise-damping components. As an additional benefit, the exhaust back pressure can be lowered by rationalising the silencers. Consequently, the engine runs with higher efficiency. Furthermore, customisation of engine sound can be provided under varied driving conditions, for example in regeneration mode of a particulate filter by damping the highly increasing SPL, at changing noise spectrums due to cylinder deactivation in the engine, or in hybrid technology by compensating for the impression of "partial load driving feel". The upcoming market trends enable the introduction of ANC within the exhaust field.

AUTHORS

Dipl.-Ing. Lukas Anslinger
is a Development Engineer at the Institute for Measurement and Sensor Technology in Kaiserslautern (Germany).

Dr.-Ing. Nicolas Driot
is an Innovation Engineer at Tenneco GmbH in Edenkoben (Germany).

Dr.-Ing. Xavier Robin
is Senior Application Engineer at Free Field Technologies in Mont-Saint-Guibert (Belgium).

Dr.-Ing. Khang Zhun Yeap
is a Development Engineer at the Institute for Measurement and Sensor Technology in Kaiserslautern (Germany).

The need to intensify the efforts in exhaust aftertreatment reduces the SPL in the exhaust pipe to a level which can be handled more easily by loudspeakers. Moreover, the expansion of the on-board power supply from a 12-volt system to a 48-volt system also facilitates the application of ANC within the exhaust as a result of reduced energy consumption and heat development. Tenneco is investigating system integration by using computational tools, and has therefore been initiating a strong cooperation between the Institute for Measurement and Sensor Technology (MTS) of the University of Kaiserslautern and Free Field Technologies (FFT). This article focuses on model-based system development. According to this, two different modelling approaches are being implemented: MTS has been modelling the complete system using a GT-Power model of the engine and exhaust system, coupled with a Simulink model through a physical loudspeaker model, which is driven by a real-time capable ANC algorithm; FFT has been using their acoustic simulation software Actran to build an electro-acoustic model of the loudspeaker and its direct surroundings with Finite Elements.

ANC BASIC FEATURES

First, an overview of the technical requirements of the ANC system components for use within a passenger car's exhaust system and an insight into the underlying physical concepts are given. The energy consumption of the loudspeaker is an essential factor for an ANC application within the car. The relation between the SPL to be reduced in the exhaust pipe and the required electric energy is highlighted in this section. To quantify the requirements for the loudspeaker, the SPL curves of the dominant engine orders within the exhaust lines have been analysed. In accordance with Eq. 1, the acoustic energy can be calculated from the RMS value of the acoustic pressure. Under consideration of some physical assumptions within the exhaust and an acoustic-electric efficiency factor, the required electric power can be estimated. **TABLE 1** shows the relation between SPL and electric power for different efficiency factors within an exhaust pipe. A loudspeaker efficiency factor of 2 % implies that the loudspeaker will emit an SPL of 95 dB/W/m in a free-field room. When the loudspeaker is integrated into a housing and the sound waves are propagating inside a pipe, the total efficiency increases. Eventually, to increase the SPL by 10 dB, ten times the electric power is needed. Energy loss due to viscous damping is not taken into account. Furthermore, it should be noted that the efficiency factor of a loudspeaker is not constant over the frequency spectrum.

Eq. 1

$$P_{ac} = \frac{p_{RMS}^2}{\rho \cdot c} \cdot A$$

P_{ac}: acoustic power
p_{RMS}: RMS value of acoustic pressure
ρ: density of transmission medium
c: speed of sound in transmission medium
A: area cross-section of exhaust pipe

According to **TABLE 1**, the implementation of the system under justifiable energy consumption is only feasible for high efficiency factors due to the high SPLs within the exhaust. In addition to the poor power balance, a loudspeaker with a low efficiency factor would dissipate the energy into heat, thus involving a higher possibility of damage to the loudspeaker. The efficiency factors of loudspeakers are very low, particularly for low frequencies, where the wavelengths are much longer than the diameter of the loudspeaker diaphragm. However, large diaphragms are not feasible for this application due to limited installation space. What is more, the efficiency factor can be increased by designing a suitable housing. Via model-based development, the optimum design and placement of the loudspeaker and housing can be determined for different vehicles with low time and cost requirements.

Following the discussion of the operating energy consumption, the control strategy for achieving ANC will be highlighted. ANC is based on the concept of the destructive interference of sound waves, also known as the superposition principle. It generates a reflection of the acoustic energy, sending it back towards the engine. For this reason, when applying an ANC exhaust system at both tailpipes of a dual flow exhaust system, the two branches should be acoustically decoupled within the exhaust. Otherwise, both systems would work against each other and thus full acoustic noise reduction cannot be achieved. The control algorithm, which varies the phase and amplitude of the sound wave emitted by the loudspeaker to achieve cancellation, is a crucial part in the design of an ANC system. There are several approaches for ANC control algorithms [1, 2]. A well-proven possibility is to use an adaptive FIR filter. Variations of the FxLMS algorithm are especially suitable. The basic principle of this algorithm is explained below. First, the dominant order frequencies are derived from the current engine speed. Thereby, a reference signal can be derived, which will be emitted by the loudspeaker after being altered in its amplitude and phase by an adaptive filter. Then, the emitted sound wave interferes with the engine order. The resulting sound wave is measured at the end of the tail pipe by a pressure sensor. Since the sensor signal includes the information of the superposed sound waves and if cancellation has been achieved, the filter is adapted according to the least mean square (LMS) value of

Efficiency in %	SPL to be achieved in the exhaust pipe: 135 dB	SPL to be achieved in the exhaust pipe: 140 dB	SPL to be achieved in the exhaust pipe: 145 dB	SPL to be achieved in the exhaust pipe: 150 dB
0.3	28.9 watts	91.3 watts	288.7 watts	912.8 watts
0.4	21.7 watts	68.5 watts	216.5 watts	684.6 watts
0.7	12.4 watts	39.1 watts	123.7 watts	391.2 watts
1	8.66 watts	27.4 watts	86.6 watts	273.8 watts
2	4.33 watts	13.7 watts	43.3 watts	136.9 watts

TABLE 1 Required electric power to generate favoured SPL within the exhaust pipe at different total efficiencies (©Tenneco)

the residual engine order. The calculation, which represents the adaptation process, is shown in Eq. 2. For the FxLMS algorithm, the transfer path from the loudspeaker to the error sensor, also referred to as the secondary path, is additionally taken into account to consider the phase shift and amplitude variation between the actuator and sensor. Since the secondary path is a critical component of the algorithm regarding system stability, an investigation to identify the influences of temperature and exhaust mass flow changes on the transmission behaviour was performed. The information flow of the FxLMS algorithm, embedded in a simulation model, which will be discussed in the next section, is shown in **FIGURE 1**.

Eq. 2

$$w(n+1) = \alpha \cdot w(n) - \mu \cdot \frac{\delta e^2}{\delta w}$$

w: filter weights
n: time step
δ: memory factor
μ: step width
e: control deviation

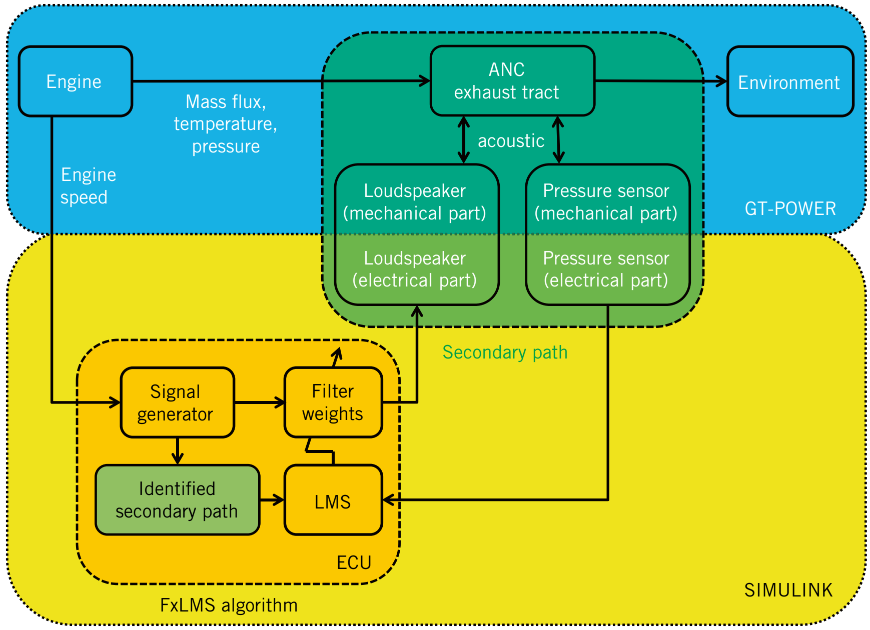


FIGURE 1 Coupled GT-Simulink model of the ANC system (© Tenneco)

ANC SIMULATION

An ANC system within the exhaust pipe environment depicts a complex mechatronic system with manifold influencing factors. Thus, model-based development approaches are important for gaining knowledge about the significant physical effects and subsequently for predicting the system's capabilities under physical restrictions and state-of-the-art criteria in advance. Different modelling approaches provide diverse benefits in the system representation. In the 1D GT-Simulink model, full system integration was investigated, whereas the 3D Actran model was focused on the loudspeaker component and its surroundings.

GT-Power is an established tool for engine and exhaust flow simulation in the automotive sector. Thus, it is predestined for simulating the corresponding parts of the ANC system, including the mechanical-acoustic interaction between the exhaust gas and the actuator or sensor. However, the electrical parts of the loudspeaker and pressure sensor, as well as the adaptive filter algorithm, are described in Simulink. Hence, the loudspeaker represents the interface between both software tools. Eq. 3 and 4 show the coupled differential equations for the mechanical and electrical parts of the loudspeaker. Thus, the fluid-structure interaction between the loudspeaker and the transmission medium is taken into account. Moreover, including the control loop into the model provides a better understanding of the noise cancellation mechanisms. Furthermore, the GT model contains benchmarked systems from the engine to the exhaust line. Hence, it can be used to test the same algorithms that are also used in the test vehicles. **FIGURE 1** shows the structure of the ANC simulation platform using a coupled GT-Simulink model.

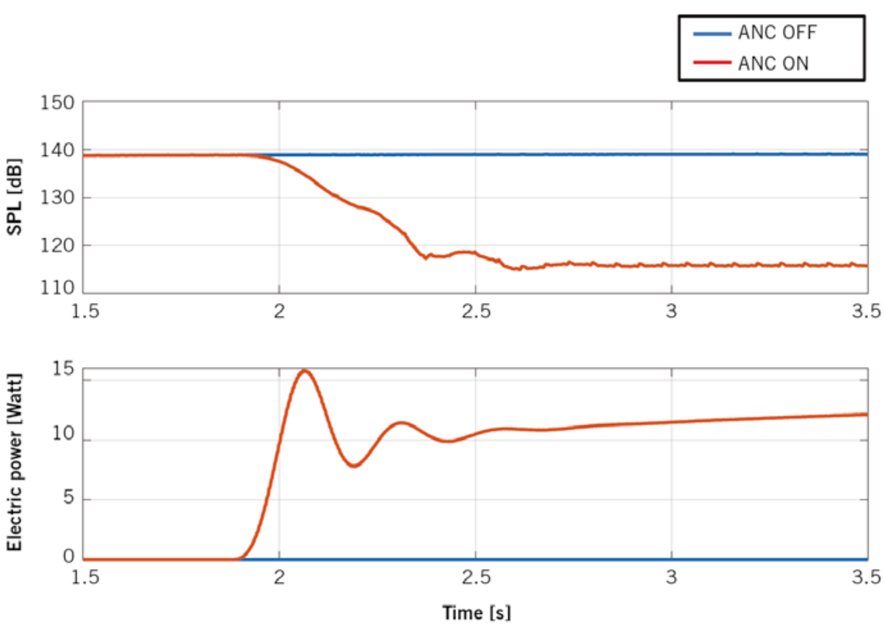


FIGURE 2 ANC simulation results of a GT-Simulink model at a constant engine speed of 2500 rpm (© Tenneco)

Eq. 3	$m \cdot \ddot{x} + d \cdot \dot{x} + c \cdot x = BL \cdot I - A \cdot p_{exh}$ x: displacement, velocity, acceleration I: current p_{exh}: acoustic pressure at diaphragm m: mass d: damping coefficient c: spring stiffness BL: force factor A: effective projected area of diaphragm

Eq. 4	$L \cdot \dot{I} + R \cdot I + BL \cdot \dot{x} = U_E$ x: displacement I: current U_E: input voltage R: electrical resistance BL: force factor

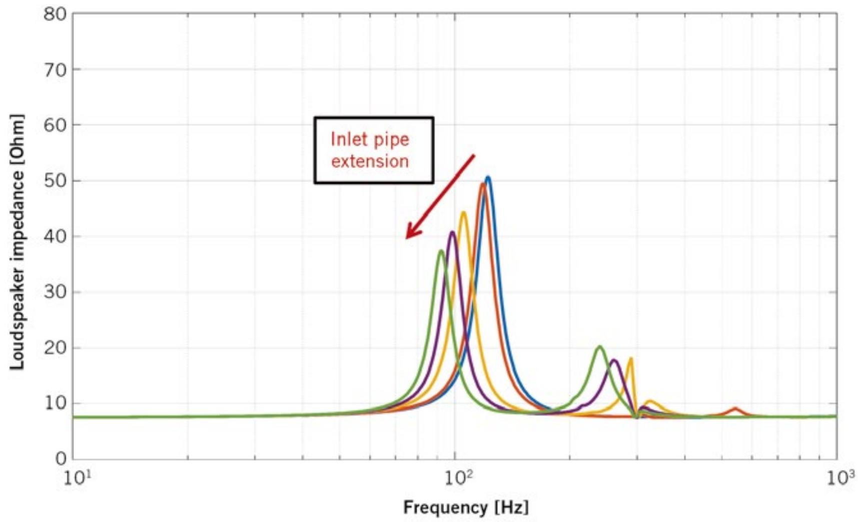


FIGURE 3 Loudspeaker impedance for different inlet pipe lengths from the loudspeaker to the exhaust pipe, computed with Actran (© Tenneco)

Ensuring stability under various boundary conditions is an important aspect of an ANC system within the exhaust. The impact of several hundred degrees of temperature variation and mass flow changes in the exhaust has a tremendous influence on the secondary path and thus on the system stability.

Phase deviation	Noise reduction with loudspeaker potential to engine order: Equal	Noise reduction with loudspeaker potential to engine order: -1 dB	Noise reduction with loudspeaker potential to engine order: -3 dB	Noise reduction with loudspeaker potential to engine order: -6 dB
0°	∞	19 dB	11 dB	6 dB
5°	21 dB	17 dB	10 dB	6 dB
10°	15 dB	14 dB	9.8 dB	5.8 dB
15°	12 dB	11 dB	8.8 dB	5.5 dB
20°	9.2 dB	9.2 dB	7.7 dB	5.1 dB

TABLE 2 Influence of phase deviation / loudspeaker with insufficient power

To ensure functionality under all operating conditions, those changes have to be considered within the algorithm. Identifying the effects under ideal conditions is one of the advantages of the model-based system design. **FIGURE 2** shows some examples of ANC simulation results when the dominant engine order at a constant engine speed of 2500 rpm is reduced.

Although many influences on the system behaviour, such as the positioning of the actuator and sensor, can be examined using a coupled GT-Simulink model, effects resulting from complex loudspeaker geometries and viscous air damping in the loudspeaker housing cannot be captured in 1D simulations. Those non-trivial influences can only be fully observed using 3D tools. In Actran, the loudspeaker, including its housing and the surroundings of the rear exhaust system, is modelled under consideration of appropriate material properties. The 3D simulation environment fully incorporates the complex fluid structure coupling with respect to the loudspeaker geometry. The electric circuit of the loudspeaker is also modelled. The electromechanical behaviour of the modelled system has been validated with experimental measurements in collaboration with Tenneco. The correlation is based on the comparison of the loudspeaker impedance in different prototype housings, see **FIGURE 3**. Hence, it is possible to predict the efficiency of the system.

The superposition principle was also simulated in Actran, emitting a harmonic wave from the engine side and an anti-phase counterpart from the loudspeaker. To quantify the influences of poor amplitude and phase adaption, **TABLE 2** shows the noise reduction of an engine order due to a cancelling sound wave for increasing amplitude and phase deviations from anti-resonance.

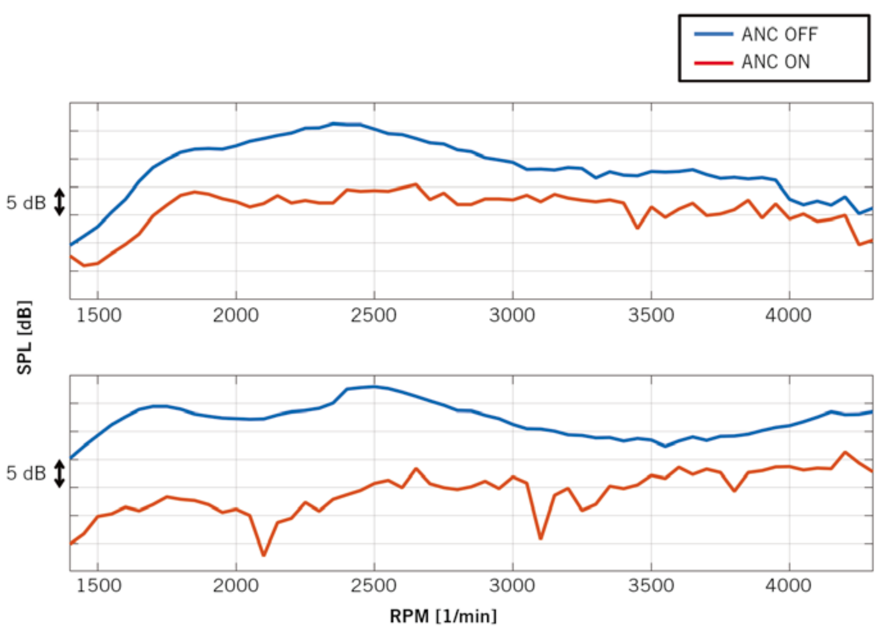


FIGURE 4 SPL of dominant engine order for full load (top) and overrun (bottom) of a 4-cylinder diesel vehicle on an acoustic roller dynamometer (© Tenneco)

CONCLUSION

Finally, some examples of the performance of a developed ANC prototype system integrated into a test vehicle will be demonstrated. For this purpose, the ANC algorithm, which has been successfully implemented and tested in the GT-Simulink model, was transferred to the test vehicle. The test runs were performed on an acoustic roller dynamometer. The noise reductions achieved for the second engine order for full load and overrun are shown in **FIGURE 4**.

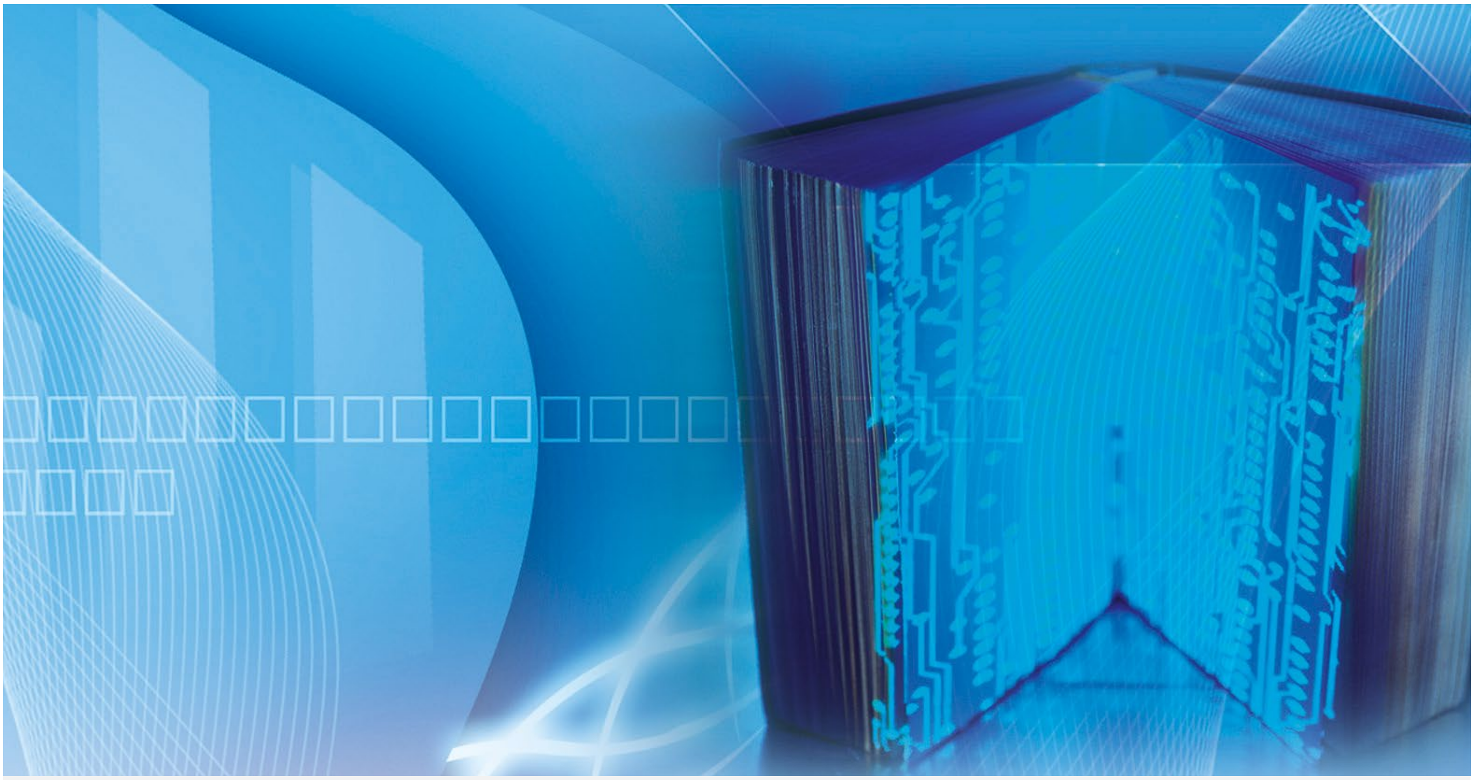
The visualised test data is already proving basic functionality, even though the system is still under development. Since the control algorithm is shown to perform effectively in the vehicle tests as well as in the 1D GT-Simulink environments, the developed model can be considered to adequately represent full system integration of the real system, including the environmental conditions. Similarly, the behaviour of the Actran model in respect of impedance and noise reduction matches the experimental measurements and the physical assumptions. Therefore, the 3D Actran model is beneficial for gaining further knowledge of the complex fluid-structure interaction between the loudspeaker and its surroundings.

REFERENCES
[1] Kuo, Sen M and Morgan, Dennis R: Active Noise Control Systems. John Wiley, New York, 1996
[2] Hansen, Colin H: Understanding Active Noise Cancellation. Taylor & Francis, Abingdon, 2001

THANKS

M.Eng. Gai Vo Thi, Dipl.-Ing. Francois Torner, Prof. Dr.-Ing. Jörg Seewig

Springer springer.com



Springer eBooks

Die weltweit größte E-Book-Sammlung für Wissenschaft, Medizin und Technik

- Unverzichtbares Wissen
- Fortdauernder Zugriff, inklusive Archivrecht
- Keine Begrenzung der Anzahl der Nutzer sowie volle Druck- und Download-Funktionalität
- Von jedem Endgerät immer und überall zugänglich – integriert in SpringerLink

#Books Change

Besuchen Sie: springer.com/ebooks

A19895