Reduction of Power Train Induced Vehicle Exterior Noise by Piezo-Foil Technology

Norbert ALT
Dr.-Ing.
FEV Motorentechnik
Aachen, Germany
alt@fev.de

Hans-Peter LAHEY
Dipl.-Ing.
FEV Motorentechnik
Aachen, Germany
lahey@fev.de

Jack NEHL
Dipl.-Ing
FEV Motorentechnik
Aachen, Germany
nehl@fev.de

Christoph NUSSMANN
Dipl.-Ing.
FEV Motorentechnik
Aachen, Germany
nussmann@fev.de

Jürgen WEISER
Dr.-Ing.
IGAM
Madgeburg, Germany
weiser@igam.de

Abstract

Rail, aircraft and road traffic noise are more and more in the focus of public discussion. Especially road traffic noise in the cities is perceived as stress for human being. Compared to secondary noise reduction approaches e.g. noise protection windows, silent roadbed up to downtown driving ban etc. primary approaches focusing on the very vehicle noise sources are most promising.

In the city the power train represents one of the major vehicle exterior noise sources with the oil pan contributing up to 40% of overall power train sound emission. Efficient noise reduction, therefore, deals with oil pan noise reduction as primary goal. Besides structural optimisation, what is limited by e.g. light-weight design and package constraints, active noise reduction by piezo-foil technology to suppress oil pan vibration induced noise promises a significant noise reduction potential.

The paper reports about activities in the EU sponsored InMar project (Intelligent Materials for Active Noise Reduction) and gives insights in application and experiences with the piezo-foil technology. The noise reduction potential of a ANR oil pan system is discussed with regard to power train and vehicle as well as its advantages compared to conventional improvement approaches in terms of efficiency, costs etc.

1. Introduction

Noise is more and more in the focus of public discussion as it represents a major source of environmental pollution especially in the cities. In Europe more than 100 million people are affected by noise leading from reduction in cognitive performance up to severe deterioration of human health and an economic loss of more than 10 billion Euros per year is generated (/1/). Road traffic noise represents for human being the most affecting noise source as documented in Figure 1.

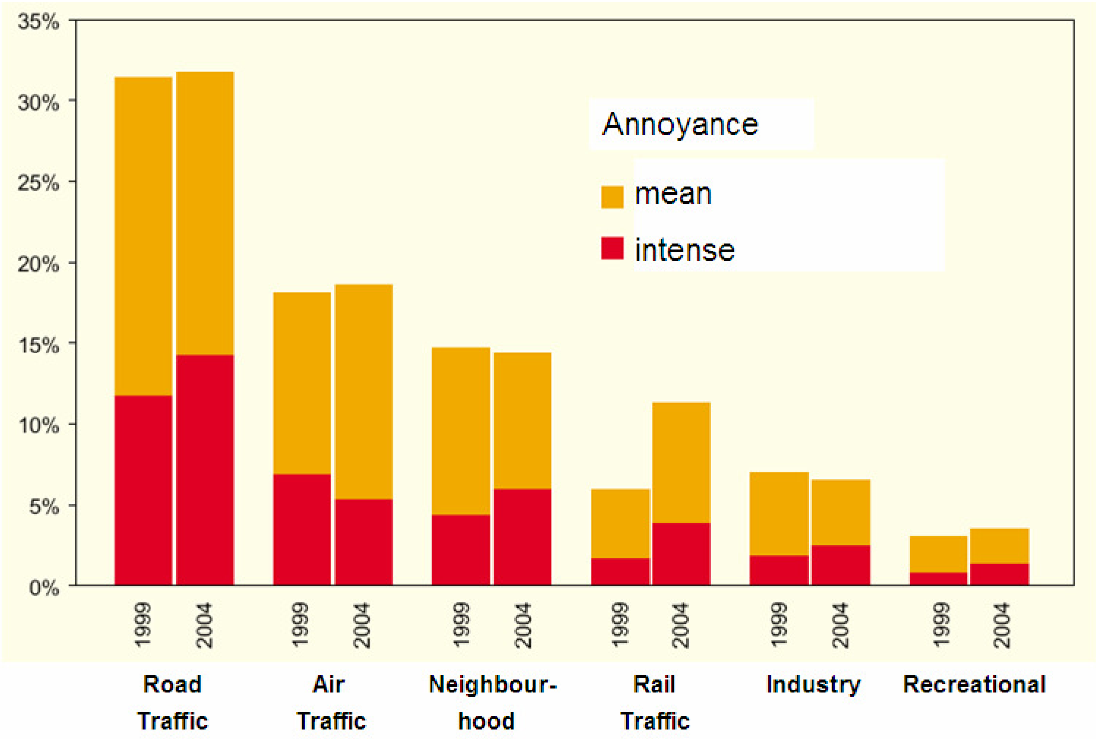

Fig. 1: Road traffic represents the most annoying noise source in environment (source: LfU)

The European Commission, therefore, started in the beginning of 2004 an Integrated Project aiming at the development of active noise and vibration control systems to reduce the noise emission by road and rail traffic and the corresponding infrastructure. This project – called Intelligent Materials for Active Noise Reduction (InMAR) – incorporates a network of in total 41 research and development as well as industrial partners and is divided into two sections:

Technical Areas: Research and development of
- new, complex multi functional materials (smart materials)
- actuator and sensor systems for "real world" ambient conditions
- appropriate production technologies
- control and power electronics for active systems
- technologies for systems integration
- methods for evaluation of systems reliability

Application Scenarios: System development and integration for reduction of
- noise emission of automotive and train vehicles
- noise in vehicle cabin and buildings

In the Work Area 4.2 – as one part within the Application Scenario "Noise Reduction in Automotives" – several ANR systems for power train application are under investigation:

- encapsulation by active shielding
- vibration isolation by active mounts
- "Thin wall structures" active damping

This paper deals with the latter, i.e. the actual status of an ANR system development for thin wall structures with the oil pan as an example.

Power Train Induced Vehicle Noise

Vehicle Exterior Noise Sources

The automotive vehicle incorporates a multitude of possible noise sources contributing to the vehicle overall exterior noise depending on vehicle operating condition, power train speed and load condition, respectively. In urban traffic the power train – as documented in Figure 2 – represents the pre-dominating vehicle noise source, i.e. in the low and mid vehicle speed range especially during vehicle acceleration.

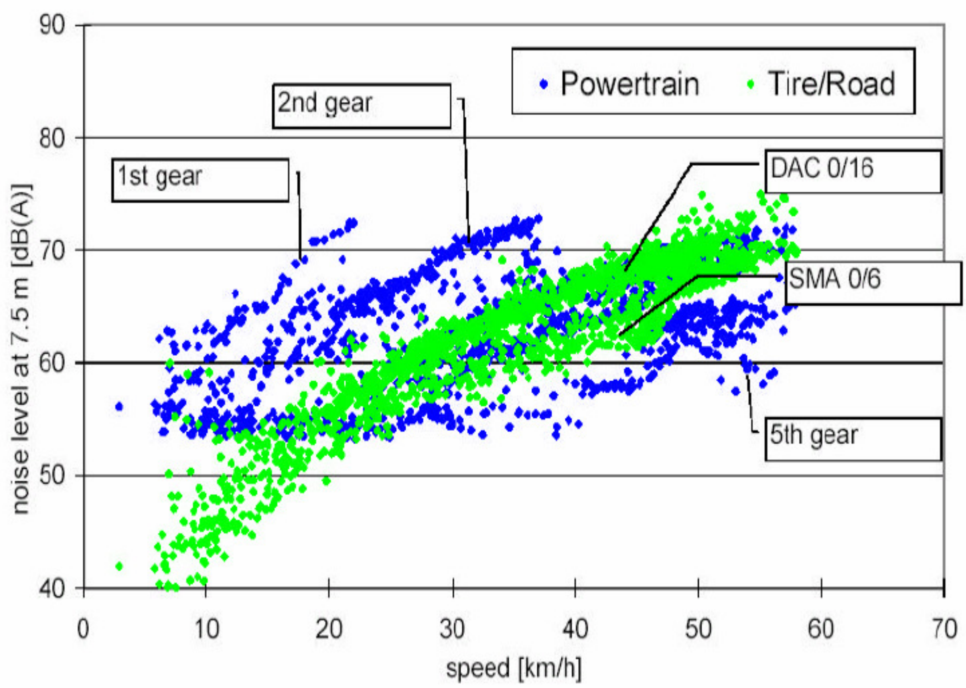

Fig. 2: Urban traffic, separation of power train and tire/road induced vehicle exterior noise /2/

The noise and vibration generated by the power train affects both, interior as well as exterior noise (see Figure 3). Its contribution to the vehicle exterior noise mainly results from directly emitted power train noise whereas the interior noise is due to both, power train noise transmitted via airborne transfer paths (e.g. firewall) into the cabin and vibration transferred via the power train mountings and radiated by structure-borne noise excited chassis components (e.g. dashboard). Additionally, the interior vibration comfort (e.g. seats, steering wheel, gear shift leaver etc.) is influenced by power train vibration, too.

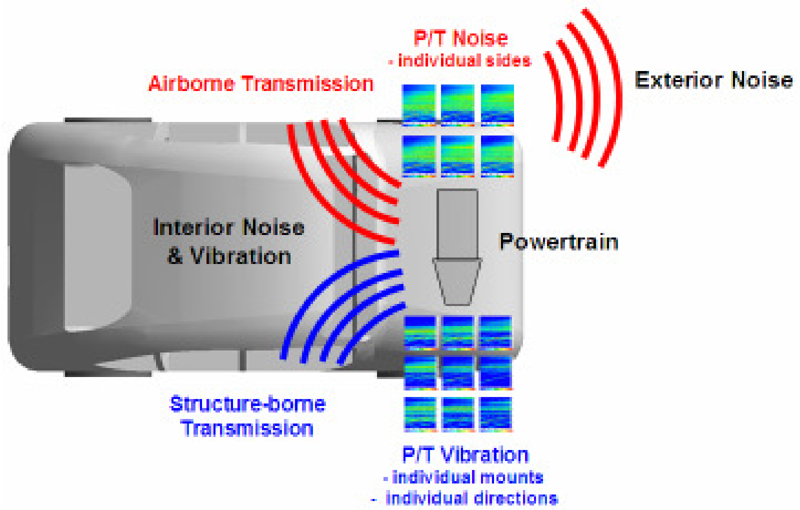

Fig. 3: Power train noise and vibration transmission in vehicle (source: FEV)

Based upon hybrid simulation tools (combination of analytical and experimental methods) the contribution of the individual power train components and the relevance of noise and vibration transfer paths involved can be analysed for interior noise and vibration (/3/) as well as for vehicle exterior noise. In Figure 4 the simulation of a vehicle pass-by noise test is exemplarily shown. The power train represents the major noise source in mid and high frequency range but especially in low frequency range indicated by firing order related noise contribution.

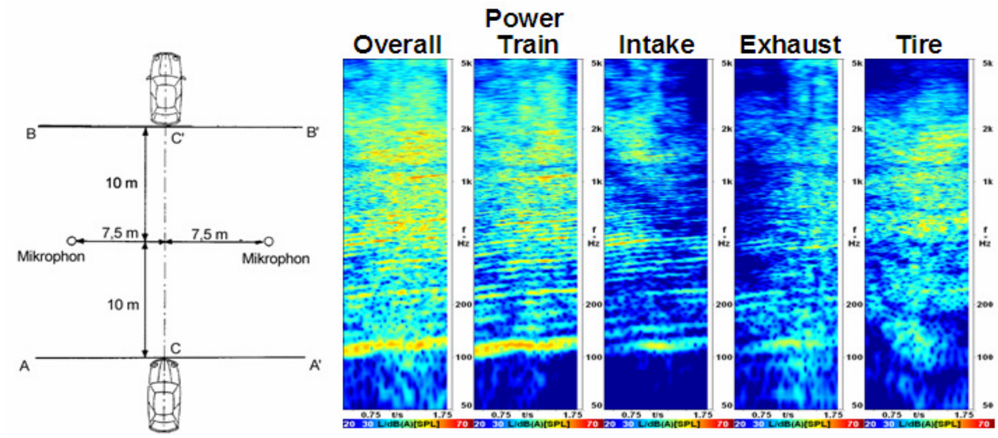

Fig. 4: Vehicle exterior noise simulation (pass-by procedure; source: FEV)

Power Train Noise Sources

The power train noise radiation typically is predominated by "thin wall structures" as e.g. oil pan, valve cover and timing drive cover. In Figure 5 the results of a near-field sound intensity measurement and the corresponding results of a combined Finite Element / Multi Body Simulation are documented for a passenger car power train as an example.

Due to its thin wall structure in combination with relatively high structure-borne excitation by engine block the oil pan exhibits the largest sound power share. The amount of oil pan noise contribution is depending on – among others – bottom end design (e.g. structural oil pan: bolted to engine block and gearbox for stiffening engine/gearbox system), oil pan design, material (cast iron, aluminium, plastic, sheet metal, SDS) and connection to engine (e.g. decoupled oil pan). Typically, most sensitive with respect to noise emission is a structural oil pan made of aluminium.

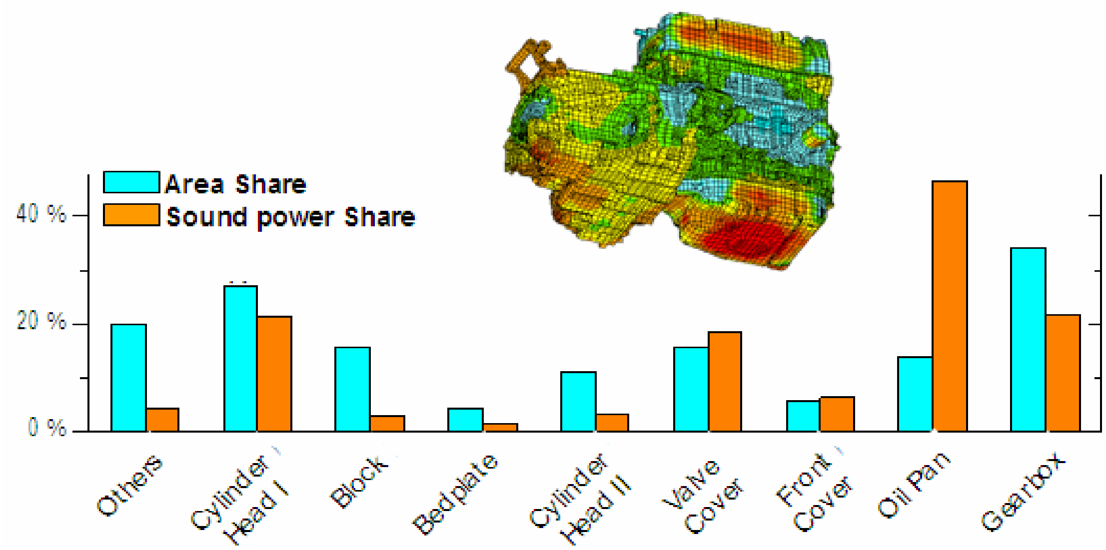

Fig. 5: Power train component noise contribution; comparison of near-field sound intensity analysis and combined FEM/MBS simulation (source: FEV)

The valve cover might contribute significantly to the overall sound power of a power train, too, resulting from remarkable structure vibration excitation of the cylinder head induced by the valve train dynamics and injectors (especially for Diesel engines). The amount of valve cover noise emission depends on – besides cylinder head design – cover design, material and connection to the cylinder head (e.g. decoupling).

In /4/ the power train noise reduction required to achieve the future legislative vehicle exterior noise limits for the (modified) pass-by noise test is expected to amount more than 6 dB(A). Taking into account the NVH status of current NVH optimized power train design, this represents a challenging task for the power train NVH engineers.

Oil Pan NVH Optimisation

Passive (conventional) Optimisation Measures

Structural optimisation by means of Finite Element simulation is an essential task within the development of a new power train. Besides oil pan design (e.g. contouring) and material (e.g. SDS) especially the power train bottom end concept plays a major role for oil pan NVH optimisation. The bottom end concept defines global power train stiffness as well as oil pan layout (e.g. decoupled/not decoupled) and the vibration excitation by the engine block. Several concepts are known (Figure 6: selected concepts) and have to be proven with regard to noise radiation benefit for each individual application. The structural optimisation of the oil pan often is limited by e.g. production line and package constraints, costs as well as required support for global power train stiffness. Therefore, NVH engineers are looking for advanced technologies for oil pan noise emission reduction.

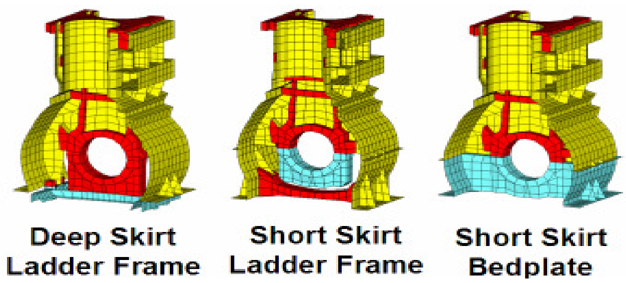

Fig. 6: Examples for power train bottom end concepts (source: FEV)

Active Optimisation Measures

With regard to automotive application several active noise reduction (ANR) systems are under development (/5/, /6/, /7/) or even now in series production (e.g. active hydro mounts). Within InMAR an ANR system for the active damping of structure-borne induced oil pan vibration is under investigation. The principle approach consists in monitoring the structural response to the excitation by a sensor and the generation of an opposite-phase actuator displacement for active damping of oil pan vibration resulting in a reduction of structure-borne noise radiation (see Figure 7).

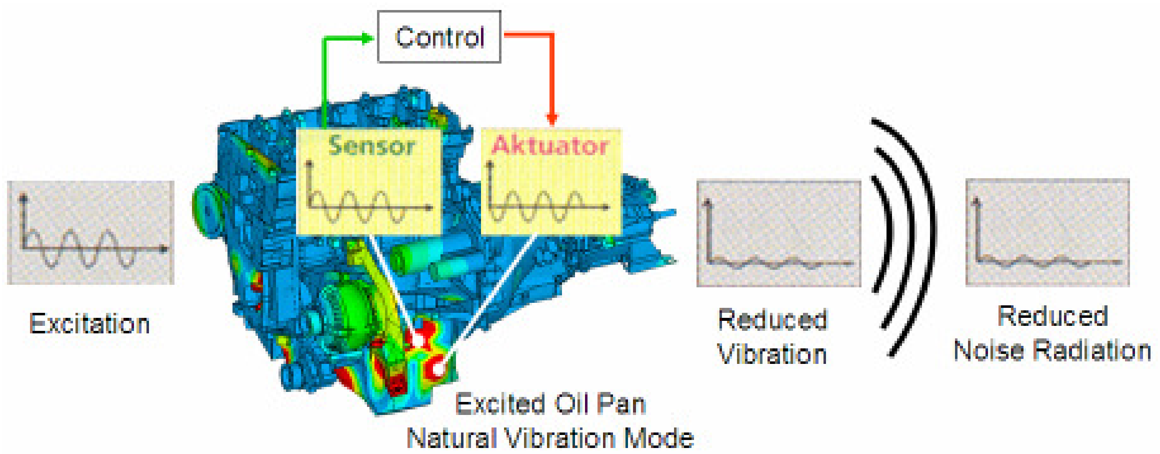

Fig. 7: Principle of oil pan active damping

The identification of the most prominent oil pan natural vibration modes under real world engine excitation as well as the definition of sensor and actuator position are performed by means of combined Finite Element (FEM: structural behaviour) and Multi Body System (MBS: power train excitation) simulation. After establishing of the excitation data at oil pan flange an oil pan / steel frame sub-model (steel frame simulates the bottom end block stiffness) was derived from full power train FEM model to enable short simulation timings for further ANR system development. In addition, the common demonstrator was made available as “work horse” to support the development of actuator layout and reliability investigation in several WA of the InMAR project. The common demonstrator in combination with the real world excitation (obtained by FEM/MBS simulation of full power train model) exhibits identical structural behaviour as the full power train model: The comparison of vibration modes reveals a good coincidence between sub-model and full power train FE model (Figure 8) and the simulation results correlate well to the experimental results (Figure 9).

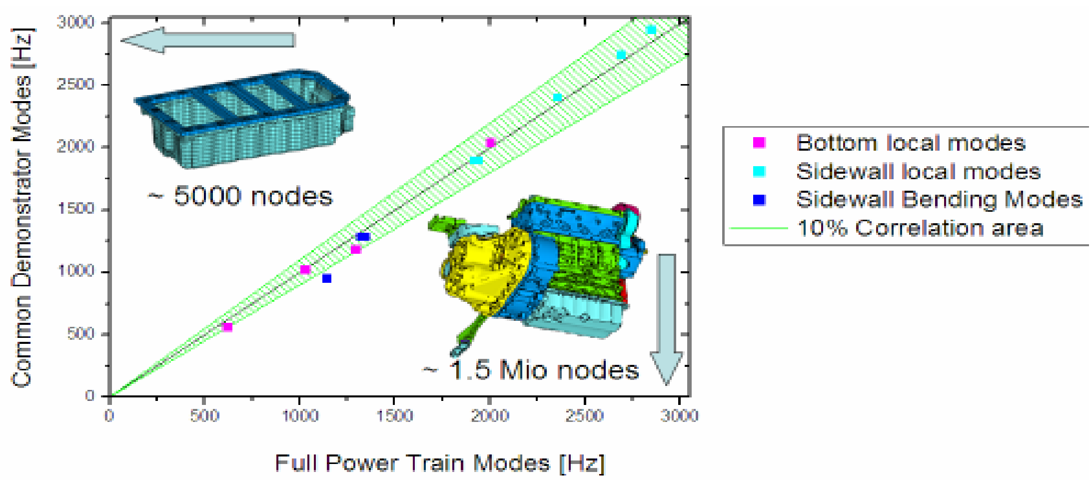

Fig. 8: Common oil pan demonstrator derived from full power train (source: FEV)

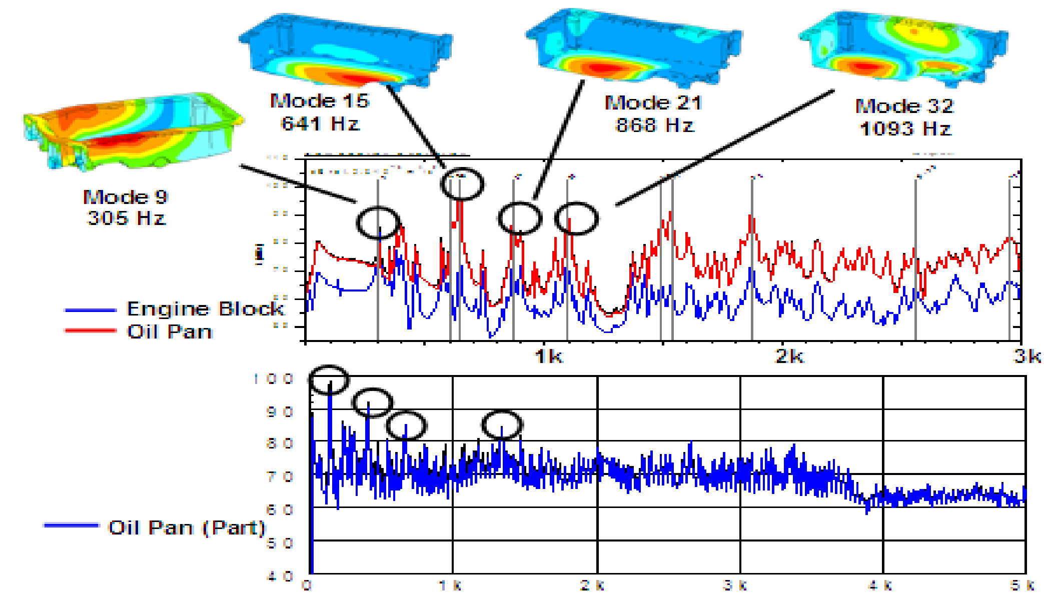

Fig. 9: Comparison of experimental and simulation results (Common Demonstrator)
Top: FEM simulation; Bottom: Near-field sound intensity analysis (source: FEV, AVL)

For active damping of oil pan vibration piezo patches are selected as actuators. A principle sketch of a piezo modul under investigation is shown in Figure 10. As the oil temperature is varying with engine speed and load high temperature piezoceramic modules are in the focus of application. Based upon experimental investigations the performance of different materials for different application temperatures are analysed and evaluated.

In Figure 11 the measurement set-up and the working diagram for a selected material (Argilllon Vibrit 420) as an example are documented.

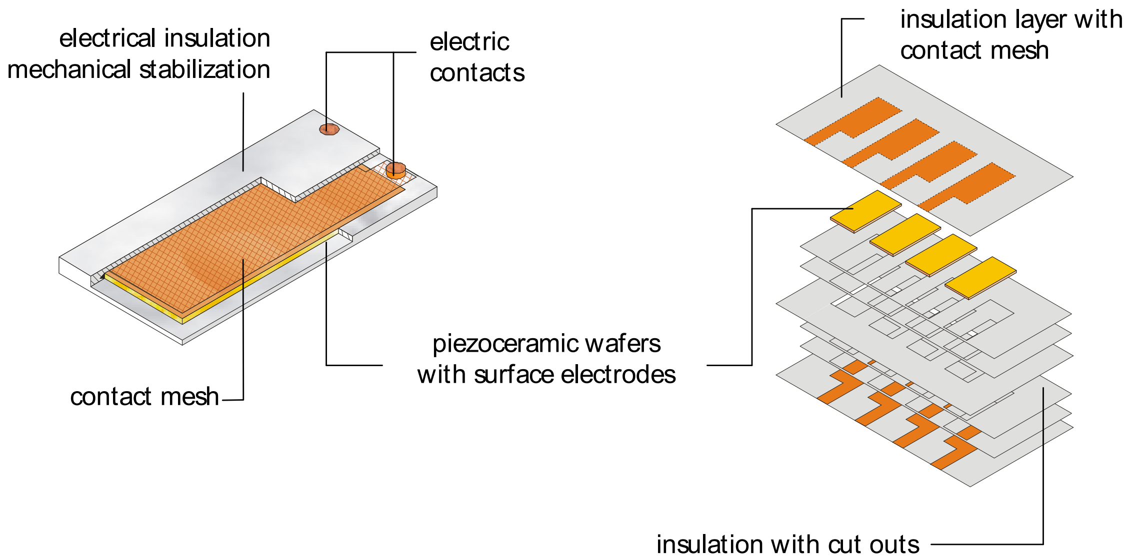

Fig. 10: Piezoceramic patch modul (/8/)

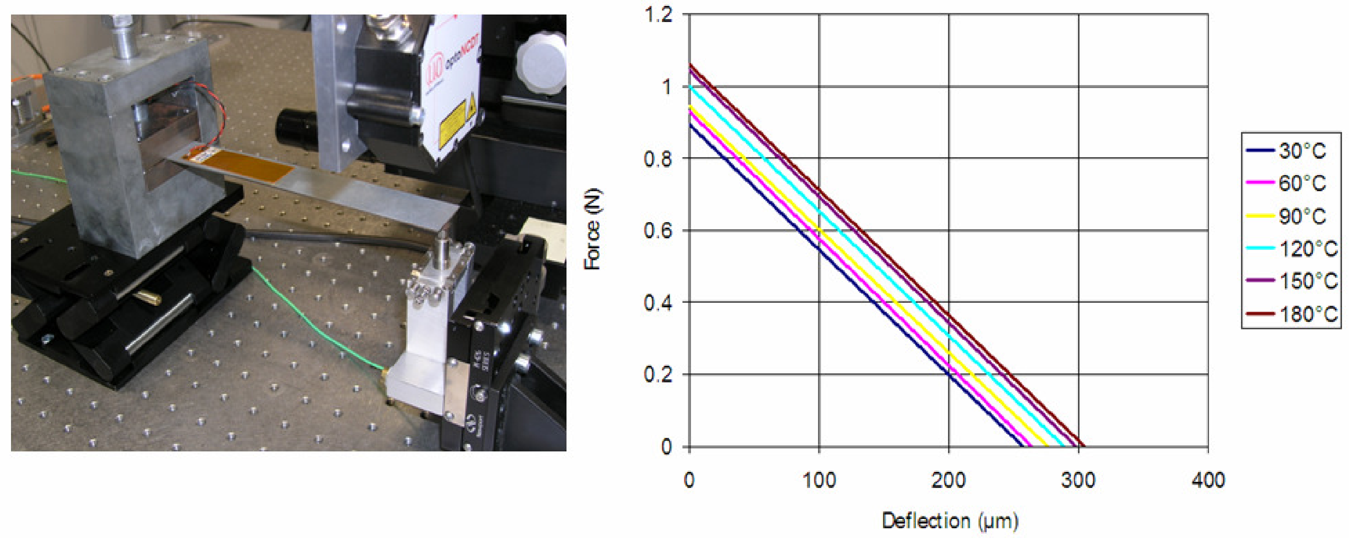

Fig. 11: Measurement set-up and working diagram for determination of piezo modul performance (source: IKTS)

Besides experimental investigations also FEM simulations were performed to evaluate the piezo-foil performance with regard to the generation of oil pan wall vibration for "active", i.e. opposite-phase structural damping. First results showed that similar displacements compared to oil pan wall natural vibration amplitudes are achievable by the piezo modules. In Figure 12 FEM simulation results with regard to piezo foil induced oil pan displacements are depicted.

In accordance to experimental and analytical results obtained for the full power train the best benefit by the actuators is achievable for the application at bottom oil pan side. MATLAB/Simulink calculations revealed a 40dB structural damping effect for local oil pan vibration modes. However, these analytical results do not yet incorporate effects as e.g. oil volume damping effects, dynamic actuator behaviour under real world application, piezoceramic modul fixation, etc.

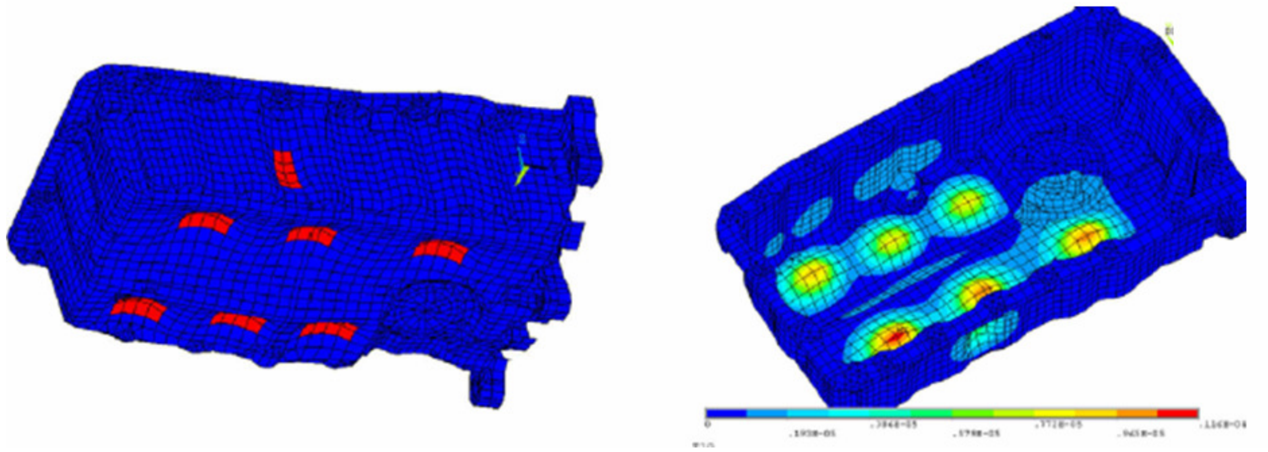

Fig. 12: FEM simulation of piezo modul induced oil pan displacements (source: IGAM)

Evaluation of Active and Passive Oil Pan Noise Reduction Measures

The introduction of an ANR system for automotive power train oil pan application in mass production – besides technical and costs challenges - finally depends on the achievable additional customer benefit in comparison to the conventional passive optimisation measures.
Table 1 reflects some aspects dealing with NVH benefit, cost and other features relevant for oil pan application. Of course, not all aspects are included in this rough overview.

Measures	NVH benefit	Costs	Robustness	Maintenance (service)	package	Fuel consumption (CO_2)	Oil temperature
Structural Optimisation (e.g. contouring)	base	base	base	base	base	base	base
Material (e.g. magnesium)	+	-	+/-	+/-	+/-	+	+/-
decoupling	+	-	-	-	-	+/-	+/-
Encapsulation (@ P/T or vehicle)	++	- -	-	- -	- -	- -	- -
ANR System (actuator, sensor, control, power supply)	++	- (?)	(?)	-	-	+/-	+/-

++: much better +: better +/-: similar -: worse - - : much worse

Table 1: Comparison of passive and active oil pan noise reduction measures (source: FEV)

It becomes clear that an ANR system exhibits promising NVH benefit compared to the actual noise reduction measures even the costs of an ANR system in mass production and its robustness in real world automotive application are not known today. In comparison to the encapsulation benefits are expected especially with regard to package, oil temperature and fuel consumption (due to lower weight). In principle, the expected promising NVH benefit will be also achievable for other power train "thin wall structures" as e.g. valve and timing drive cover. However, the final acceptance in automotive industry will strongly depend on the challenges with regard to costs and robustness.

Summary

Road traffic noise is perceived as stress for human being especially in the cities. The power train represents one major vehicle exterior noise source with the oil pan contributing up to 40% of overall power train sound emission. The paper reports about activities in the EU sponsored InMAR project (Intelligent Materials for Active Noise Reduction) and gives insights in application and experiences with piezo module technology.

The approach consists in active damping of structure-borne induced oil pan noise radiation: Monitoring the oil pan structural response to engine block excitation by a sensor and generation of an opposite-phase oil pan wall vibration by an actuator. For the layout and development of the piezoceramic foil based ANR system a common oil pan demonstrator was derived from the full power train FE model serving as “work horse” in several InMAR work areas.

The piezo module selection and layout is supported by analytical and experimental investigation with focus on positioning and required performance. First simulation results exhibit sufficient displacements and forces for effective active structural damping of relevant oil pan vibration modes but have to be proved by experiments under real world condition in the future.

Compared to conventional (passive) noise reduction measures the ANR system promises significant noise reduction potential for the oil pan. However, the introduction into automotive mass production is mainly depending on customer benefit, i. e. challenging tasks with regard to acceptable system costs and reliability under automotive environment conditions.

The authors like to thank the WA partners for their cooperation and the abandonment of project results for this paper.

References:

/1/ T. Bein, H. Hanselka: Das Integrierte Projekt „Intelligent Materials for Active Noise Reduction-InMAR“- Ein Überblick, Adaptronic Congress 2004

/2/ M+P-NL Position Paper ISO/TC43/SC1-WG42 on part 2 ISO 362

/3/ G. Eisele, K. Wolff, N. Alt, M. Hüser: Application of Vehicle Interior Noise Simulation (VINS) for NVH Analysis of a Passenger Car, SAE 2005-01-2514

/4/ B. Spessert: Möglichkeiten zur Reduktion des Strassenverkehrslärms; VCD Tagungsband „Leise in die Zukunft”, Teil 1, 2003

/5/ J. Melcher, V. Krajenski, H. Hanselka: Adaptronik im Automobilbau, Potentiale, Chancen und Notwendigkeiten, ATZ 100, 1998

/6/ R. Käsler, H. Prinzler, F. Ridderskamp, M. Merz: Schwingungstechnisches und akustisches Potential von Lagerungskonzepten bei innovativen Antrieben, 10. Aachener Kolloquium Fahrzeug- und Motorentechnik, 2001

/7/ A. Gennesseaux: Research for New Vibration Isolation Techniques: From Hydro-Mounts to Active Mounts, SAE 931324

/8/ P. Wierach, D. Sachau, A. Schönecker: Design and Manufacturing of Complex Adaptive structures with Piezoceramic Patch Actuators, IMECE 2001