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Noise Reduction by Intelligent Materials Final Results of the IP InMAR

Thilo Bein*, Holger Hanselka, Tobias Melz
Fraunhofer-Institute for Structural Durability and System Reliability LBF; Germany
Bartningstr. 53, 64289 Darmstadt, +49-6151-705463, thilo.bein@lbf.fraunhofer.de

ABSTRACT

Noise is a serious form of environmental pollution believed to affect the lives of some 100 million European citizens. The cost of the associated damage is estimated at more than ten billion euro per year. The IP 'Intelligent materials for active noise reduction' (InMAR) was addressing this problems over the last 4 years aiming to reduce noise levels associated with road and rail transport, both interior and exterior, as well as associated infrastructure such as bridges in applying smart structure technologies. Smart structure technology enables new and innovative approaches to optimise engineered structures with increased functionality in all fields of mechanical engineering. Basically, an increased functionality can be achieved by embedding sensors and actuators in load-carrying structures combined with advanced control strategies. Over the last decades, these smart structures are mostly applied to noise and vibration control in high-cost light weight components where nowadays more and more light weight mass products such as automotives have to be considered. But particular light weight design in automotives is facing contradicting requirements such as safety, comfort and weight which cannot be overcome with conventional design rules. Particular noise, either from the vehicle radiated noise or vehicle interior noise will be one of the most challenging specifications for light weight vehicles only are met by active noise reduction concepts. As underlying principle for noise reduction concepts, Active Structural Acoustic Control (ASAC) is primarily being considered. Applying ASAC concepts, the noise radiation is controlled either by controlling the structural vibration of the radiating structure or by interrupting the structure borne sound path. Beside the challenges in designing a suitable control strategy, special focus has to be given to intelligent material systems as construction material or to high performing actuator systems which can be integrated in the vehicle body and capable of withstanding high and harsh operational loads. In this paper, a summary of the final results obtained in the IP InMAR will be presented. Particularly the concepts realized for automotive and train applications such as in power trains will be discussed with respect to achieved noise reductions and their potential for commercialization.

Keywords: intelligent materials**,** active structural acoustic control, system reliability, active mounts, novel electronics

1. INTRODUCTION

Progress in material research is the driving force behind innovative ideas not only in road transport but in all fields of technology. This means that the availability of new materials, their manufacturing technologies, and their implementation in products is one of the crucial factors for economic success. New materials and their manufacturing must be equally in tune with sustainability, economic viability, safety, and a high level of component and system reliability. Beyond this, material development will probably concentrate more on materials and components with multifunctional characteristics and the way they are integrated into systems. In the next decades, the focus on material research and its application will be driven by the demand for lightweight engineering, component and system reliability, energy saving, developing information technology to greater integration densities, and peripheral sensor and actuator applications coming up with integrated sensor and actuator functions.

In almost all transport modes more and more modular lightweight components are introduced and applied in different vehicle platforms including the aerospace sector. To ensure the desired properties, the characteristics of the components such as stiffness, damping, or impedance need to be adapted to the system in which they are built in without changing its functions or losing its general approval. The existing conflict between lightweight design on the one hand and passive safety and comfort requirements as well as a competitive selling price on the other hand must be solved by the introduction of intelligent material systems and the use of new flexible manufacturing processes. Furthermore, concepts of innovative modular lightweight structures need to be developed such as space frame structures allowing the integration of higher functionality for, e.g., passive safety and comfort. For this, life cycle costs and system reliability have to be evaluated carefully with regard to process engineering, manufacturing, use, and end of life to ensure the economical and ecological benefits of an intelligent lightweight design.

Both a sustainable development and the addition of higher functionality in products are to be enhanced by a noise-optimized product design. It is well known that lightweight structures tend to vibrate more easily and radiate noise on a higher level. Special effort must be made to compensate the higher noise level. This often requires additional mass, which, in turn, nullifies the lightweight design. As noise is being considered as one of the worst environmental pollutions worldwide, noise abatement concepts are demanded for various products to protect people. In the future, noise-optimized products can only be achieved by applying active noise reduction concepts based on intelligent materials that allow a lightweight design and higher functionality with respect to noise control. It must be stressed that the same technology can also be applied purely to a concurrent lightweight design by controlling the structural properties that impact the fuel consumption, exhaust emission, or safety aspects of vehicles.

Within this context, the integrated European project "InMAR – Intelligent Materials for Active noise Reduction" [1] aims to reduce noise levels associated with road and rail transport, both interior and exterior, as well as associated infrastructure such as bridges. InMAR is bringing together top research institutes and universities, OEMs (original equipment manufacturers) from the automotive and railway sectors, components producers, and eight SMEs (small and medium-sized enterprises) that specialize in smart structures and materials. The main objectives of the application scenarios are to design and develop advanced active noise reduction concepts for

- exterior noise of vehicles and trains,
- interior noise in vehicles, trains, and buildings
- and sound quality design of interiors

as cost-effective solutions for a broad-band noise reduction of 10 dB(A) or more.

2. STRUCTURE OF THE IP INMAR

In order to gap the bridge between fundamental research and applied technology the consortium of the IP InMAR consists of all leading research institutions in Europe (8 research organizations, 11 universities) in the field of smart structures and intelligent material systems as well as most of the major industries of the intended applications (23 companies), 8 of which are considered SMEs. The consortium combines researchers from various, complementary specialties and enables the cross-frontier cooperation of partners beyond their traditional tar-get markets by providing S&T excellence and by ensuring the quality of the consortium.

The scientific and technological objectives are reflected in the structure of the IP as shown in Table 1 and Figure 1 below. According to these objectives, the IP *InMAR* is structured in three complementary technology areas (sub-projects) dealing with intelligent material systems and their integration, simulation, and life-cycle aspects. These technology areas strictly concentrate on providing the enabling technology required for the application scenarios but at the same time strongly rely on the system definitions and requirements provided by them. The application scenarios again are divided into three sub-projects for application, integration, and verification in automotives, trains, and infrastructure.

Table 1. Project Structure

Cluster 1: Technology Area		**Enabling Technology ⇒ ⇐ System Requirements**	**Cluster 2: Application Scenarios**	
Sub-Project	**Work Areas**		**Sub-Project**	**Work Areas**
TA 1 Intelligent Material Systems	Material Systems		**AS 1 Noise Reduction by Automotives**	Tire & Breaks
	Actuator & Sensor Systems			Power Train
	Manufacturing			Sheet Metal Parts
	Control			Car & Truck Bodies
	Electronics			Sound Quality of Interior Noise
				Noise Transmission of Windows
TA 2 System Integration	Simulation & Optimization		**AS 2 Noise Reduction by Trains**	Wheels & Breaks
	Electronic & Control Systems			Power Train & Bogie
	System integration			Ventilation
	Characterization & Validation			
TA 3 Life-Cycle	Reliability		**AS 3 Noise Reduction by Infrastructure**	Windows & Facades
	Condition Monitoring			Bridges & Tunnels
	Recycling			Elevators

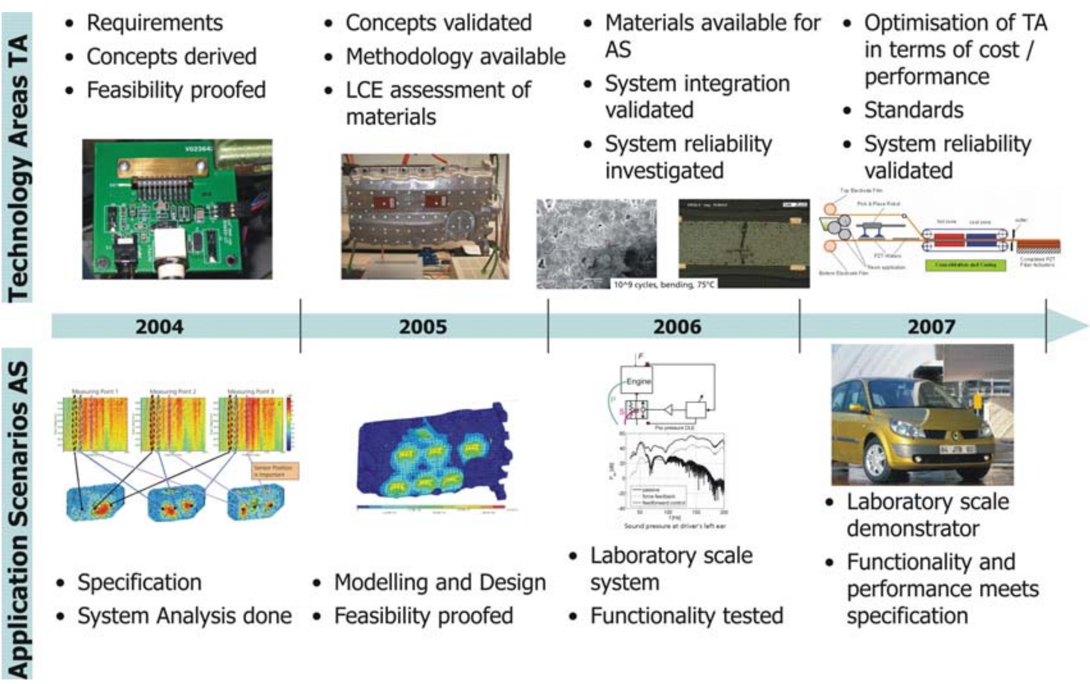

Figure 1. Timeline and Milestones of the IP InMAR

3. SELECTED RESULTS

Over the full project, all objectives of the IP InMAR have been fulfilled. Altogether, 368 deliverables and 231 milestones were made over the full project. The results clearly indicate the potential of active systems and intelligent materials systems for active noise control in a sustainable lightweight design.

In the technology areas major progress and breakthroughs have been realized with respect to performance of the material and actuator systems, manufacturing, control strategies and electronic components suitable for the intended applications. Furthermore, for the first time detailed investigations on the reliability of such systems were conducted demonstrating that the standards and requirements of the industry can be met. Besides, cost effective design tools were developed and validated allowing a much more efficient design of active systems within development process of the industry.

Regarding the applications scenarios, for all considered benchmarks the feasibility and potential of active systems for a noise reduction on 10 dB or more has been proven. The validation of the concepts resulted in laboratory-scaled demonstrators up the implementation and demonstration in vehicles. A brief overview of selected, highlighted results is given in the table below.

Table 2. Selected results

Technologies
• Acoustical optimised sandwich panel (“chessboard”) • New concept for large stroke acoustic piezo actuators. • High temperature actuator modules. • Design and realisation of integrated MEMS system prototype as a proof of concept • Scaling-up of MFC-manufacturing • Operational prototype of sound cancelling system in a package slightly bigger as a one Euro coin • Several effective approaches and tools developed. • Amplifier for piezo patches with high efficiency consisting of a Class-D amplifier with charge control and charge recovery • power electronics for integrated MEMS systems. • A 12V to 150V DC/DC converter for automotive applications • Development and validation of a multi-attribute optimization approach for active systems, including the location of SAP. • Development of a robustness analysis approach. • Control system with high-speed low-authority control extension on FPGA • sandwich piezo panel with multiple integrated power amplifiers. • Proof of reliability of active systems • Statistical investigation on correlation between cracking intensity and degradation
Applications
• Functional validation of two concepts to control break squeal. • Active system for a large engine oil pan reducing sound power by six decibel • Active control of a small engine oil pan under real operating conditions showing a sufficient performance • Active engine mount system implemented in a Renault Scenic • Development of a roof liner with integrated flat panel actuator system. • Development and integration of a working 2 seat SQ ANC system into a production vehicle. • An active clamping of the windshield for reduced noise transmission • An active damped windshield was implemented in a vehicle. • Active silencer cassettes for forced ventilated cooling or HVAC systems • SMA clutch system for self-ventilated traction motors or other engines, • Novel mounts or tuned absorbers for integrated active vibration reduction of aggregates or engines. • Integration of a strip speaker within a double glazing window for control noise transmission • An active rail fixation was assembled and tested.

3.1 Novel control and power electronics

Decentralized systems are well applicable to active vibration control of light weight panel structures which can be found for example in airplanes, cars or in casings of technical equipment. The decentralized system consists of independent control nodes which contain at least all elements of a single-input single-output (SISO) controller and a communication interface. Advantages of a decentralized architecture compared to a centralized one are a reduced cabling effort, a good scalability to different control problems and the improved robustness against defects in single control-nodes.

For this purpose, a positive position feedback (PPF) has been chosen as control law because of its simple analog design and it's good applicability in conjunction with laminar piezoelectric sensors and actuators. The controller concept has been implemented on an electronic circuit representing a single adjustable PPF controller which communicates over a Controller Area Network (CAN) with the PC. The chosen setup consists mainly of a Microcontroller (MC), a communication interface and a digitally adjustable analogue filter. Further a programmable gain amplifier (PGA) and driver unit for the piezoelectric patch actuator has been included. Fig. 3 shows principle diagram of the developed electrical circuit. For the realization of the different functions standard hardware components have been used. As power amplifier for the piezoelectric amplifier for example a high-voltage operational amplifier has been used. Fig. 4 shows the control node which has been realized as stackable printed circuit board (PCB). One PCB houses the MC and the communication interface and one PCB the adjustable analogue filter, the sensor and actuator amplifiers and the PGA.

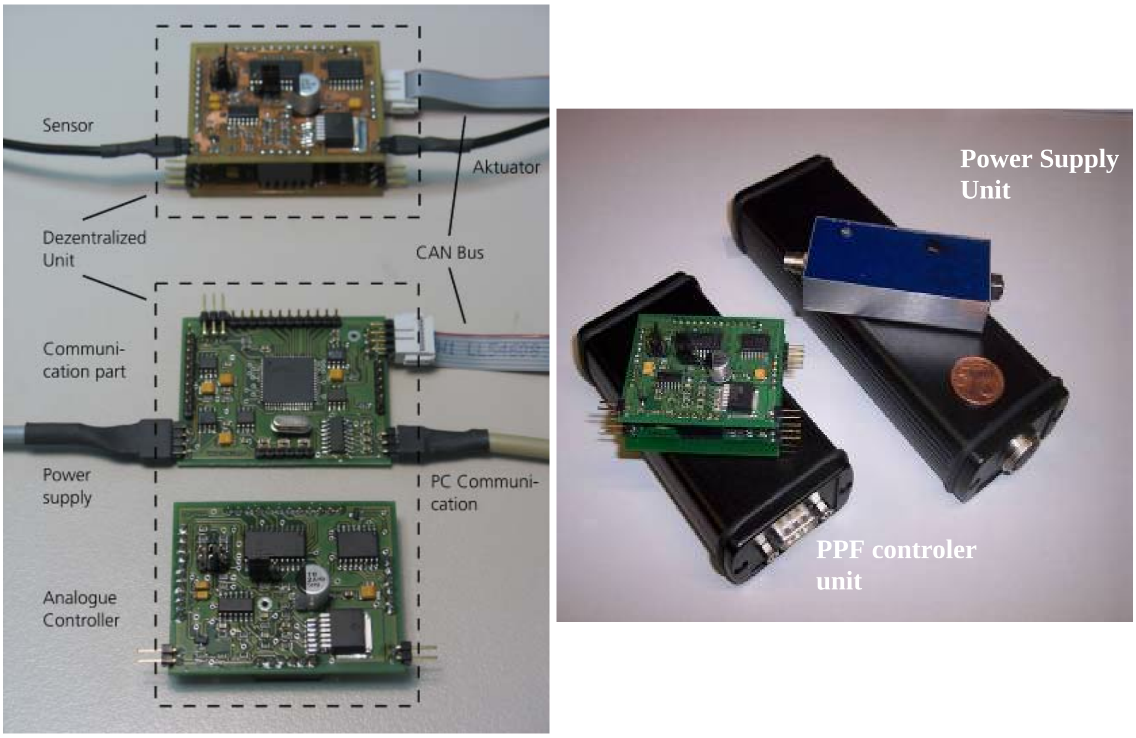

Figure 3. Novel controller and power units

Furthermore, the objective of this task was also to design miniaturized power electronics for active systems based on piezoelectric transformers. The transformer circuit (DC/DC converter) should be suited for the automotive industry, which means a 12V DC supply. This was primarily done by using low cost and easy accessible, standard "off the shelf" components. Furthermore, the design was to be as discrete as possible in order to optimize the circuits to various specifications. Beside the DC/DC converters as power supply for the 12V automotive system, also power amplifiers for piezoelectric actuators were designed (Fig. 4).

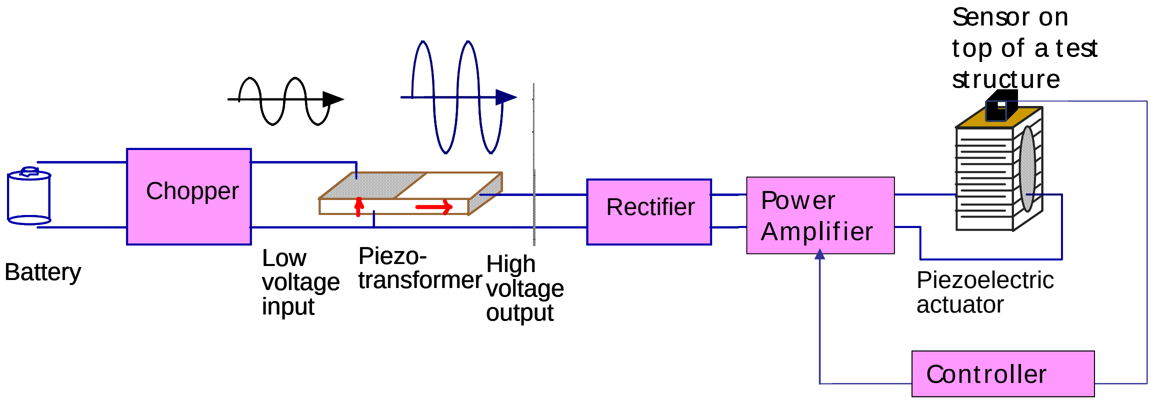

Figure 4. **The anticipated design of the test rig**

Additional developments also included the design of a low cost digital control platform based on a microcontroller with a hybrid processor (µC and DSP Kernel) and a MEM accelerometer as sensor for the mechanical test structure. Altogether, four different power supply modules for PZT actuators were build:

- Two bulky linear 315V (95mA) modules driven from the 230V main supply, as reference
- A 12V/500V supply, using a 6,5W piezo-transformer, for a cantilever beam structure
- A 12V/300V (6W) supply for the oilpan demonstrator
- A 12V/150V (6W continuous) supply for an "Integrated Interface"

The DC/DC converters were developed as a modular system, so that any output voltage can be realized. The circuits are built up with standard and low cost components. The efficiency (over 80%) was found to be better than commercial converters with a comparable output power and voltage ratings. In order to test these power supply modules a modular system for designing linear power amplifiers of different voltage and power ratings was developed. The amplifiers can be used either with bulky linear power supplies or with the miniaturized SMPS (DC/DC Converters).

Figure 5 is showing the power electronics for an integrated interface, which can be now driven from the 12V car battery. The output voltage is about 130V and the current limited to 120mA.

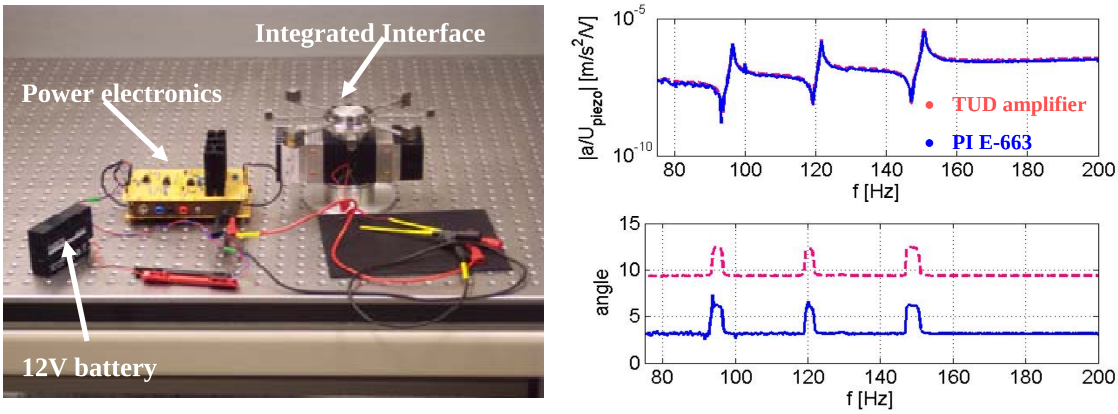

Figure 5. **The power electronics of the Integrated Interface**

The performances of these power amplifiers (SNR over 50dB for current and voltage) were found to be as good as or even better than those of commercial manufactures (Figure 5). The advantage now is that any amplifier including its power supply with almost any footprint or power and voltage rating can be built.

3.2 System Reliability

The acceptance of active systems is strongly related to their reliability. Besides catastrophic failure of the system or subsystems, degradation phenomena gradually reducing the performance are also of importance. Due to their complexity, the systems contain several sources for unreliability. Within InMar, investigations on materials as well as system level have been executed in order to elaborate methods and strategies for reliability investigation of active systems.

On system level the active oil pan demonstrator was used as one main test structure for system reliability investigations. The advantages of this choice were that the oil pan also became a main demonstrator in other work packages and consequently the technical boundary conditions for a successful set-up of the demonstrator were given. Furthermore, this application scenario offers several technical challenges for reliability investigations which are of general interest: High temperatures, aggressive environment, degradation phenomena of active materials, performance evaluation of the ability of the active system to reduce the noise radiation over the expected lifetime, derivation of complex load situations in collaboration with industrial partners (OEM’s). The work resulted in a complex test stand enabling to run all relevant operational states in the lab. Additionally, conventional reliability tools like FMEA have been applied including the present expert knowledge from several Work Areas.

To verify the reliability of an active noise control system for oil pans developed within the InMAR project, a test stand has to be developed and commissioned. A holistic system test stand reproducing all the relevant features necessary to maintain the functionality of the system were built up, Fig. 6. The test stand is able to reproduce important system parameters influencing the system perform-ance. Thus, it is possible to insert oil of different temperatures in a range between room temperature and +150 °C at different filling levels (between 0 and 4 litres).

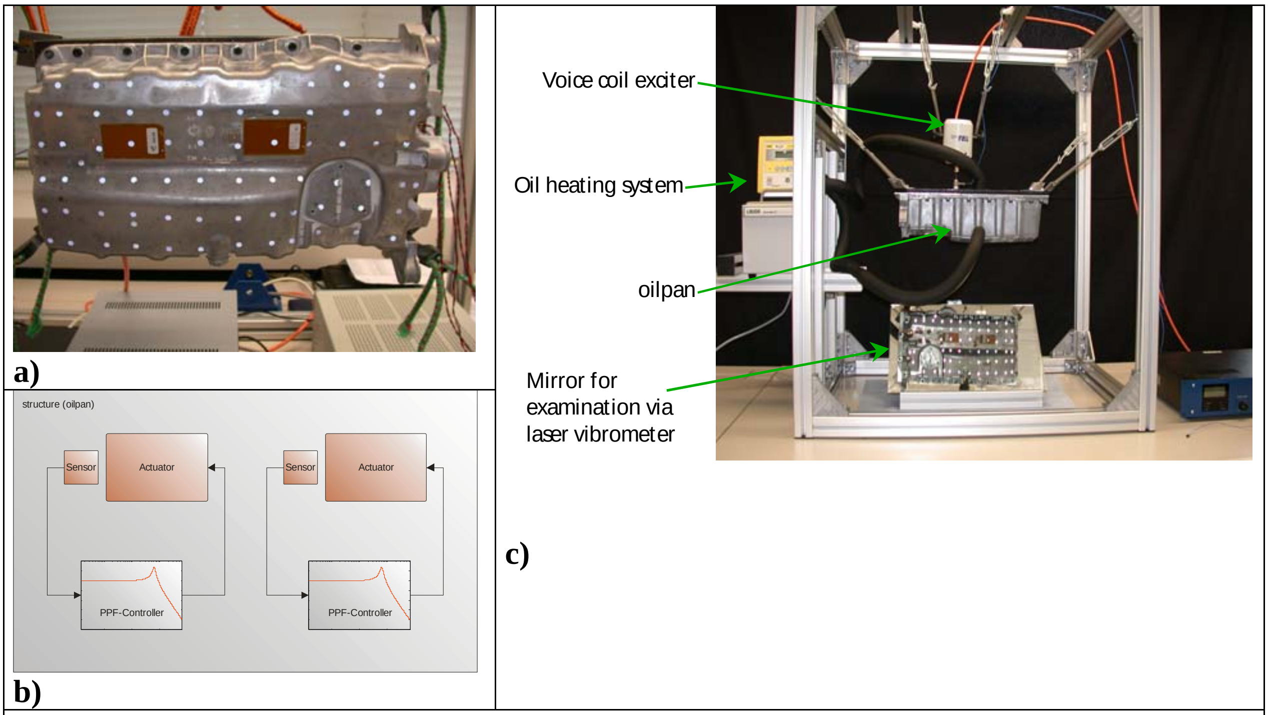

Figure 6. Set.up of the oil pan test stand. a) oil pan equipped with piezoelectric composite actuators and sensors, b) Control scheme (ppf – controller) used for 1st and 2nd eigenmode, c) test stand allowing for adjustment of different operational states as well as long term reliability. The test stand consists of an electro-dynamical excitation as well as hot oil circulation. The vibration is measured by a laser vibrometer via a mirror.

With this test stand, it is possible to adjust different operational states and parameter combinations as well as to perform long term reliability tests. The test stand has to be able to test the entire damping system composed of the oil pan, the sensors, actors and control under realistic conditions. Based on earlier works, some of the main factors which are required for realistic testing are listed beneath.

Requirements:

- Maximum oil temperature: 150°C
- Maximum oil pan temperature 135°C
- Excitation of eigenmodes up to 1000Hz
- Non contacting data logging
- Adjustable oil gauge
- Low interference with environment
- Simulation of mechanical loads caused by oil

On materials level, the strategy was to set up test procedures and –hardware based on load data based on the real application. Before and after the long term tests, microstructural investigations were done in order to correlate the state of degradation with changes in the micro- and mesostructure of the materials. Two types of innovative piezoelectric composite actuators were investigated. At an early stage of the project, Macro Fibre Composite (MFC) actuators, which were commercially available, have been tested under several boundary conditions. The tests gave a first impression on the general behaviour of composite actuators under long term conditions. Later, the high temperature piezo materials designed for the oil pan application were investigated. A complex work plan containing several critical operational states like high temperatures and aggressive media has been developed An important branch in investigation of composite actuators is the accelerated testing technique, which is necessary in order to reduce testing time as well as amount of samples. Due to this fact, the possibility of accelerate tests of composite actuators and to determine acceleration factors has been investigated as well.

As a first step, the test parameters to be chosen for experimental testing of the devices have been derived from the oil pan application scenarios. A test scenario is given by a set of parameters. The important physical parameters are Temperature, electric field, mechanical strain. The test scenario $\underline{S}$ is therefore defined as a set of maximum values for mechanical strain, electric field, temperature, as well as frequency of the excitation, and is written as

$$\underline{S} = (T, \varepsilon, E).$$

It is unclear in how far the frequency of the mechanical and / or electrical excitation may also be treated as a scaleable parameter. No experience is present in how far the frequency will influence the degradation. In this study, the frequency was not as a scaleable parameter but as a boundary condition. Chemicals are treated as a boundary condition as well.

The diagram in Fig. 7 shows the load parameters as boundaries for different load scenarios. Three different regimes can be found:

1. Oil pan working point regime
2. Acceleration regimes
3. Different failure mode regimes

It is assumed from experience made during the MFC study as well as from general knowledge on this material type that these parameters are scaleable, what means that a higher amplitude value will lead to a higher or faster damaging or degradation. The different load regimes are sketched in Fig. 7b, showing that the scaleable parameters will allow for an acceleration technique discussed in a later section.

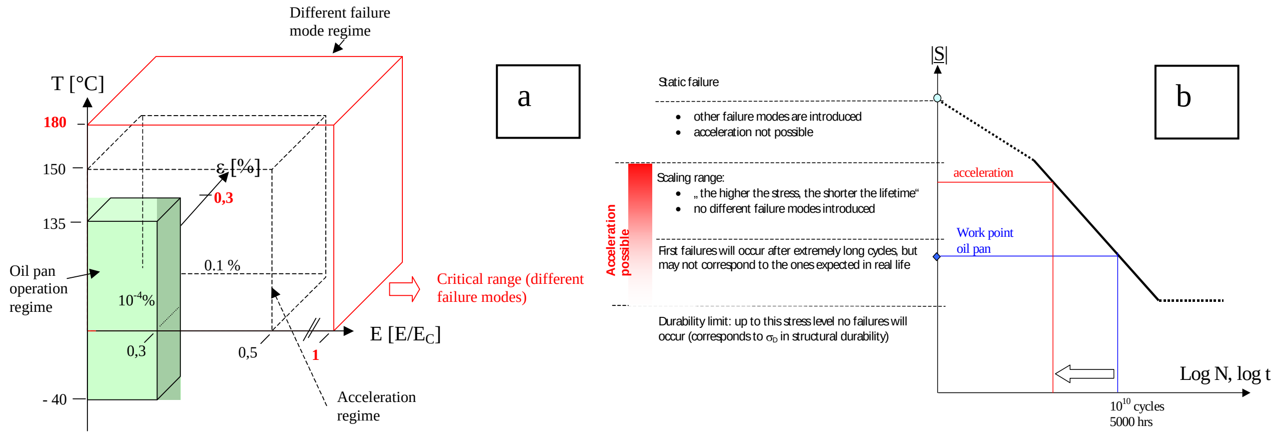

Figure 7. a) Different test scenarios S for the oil pan. The greenish box shows the normal operational range of the oil pan. The black dashed box includes a range of testing where acceleration most likely is possible (an experimental proof to this assumption is very difficult and is therefore based on experience). The red box is a boundary beyond which acceleration is not possible. Example: higher temperature than 180°C will cause failure within the matrix material of the patches. b) Schematic drawing showing the different load regimes. Acceleration is assumed to be possible in a certain range around the assumed oil pan scenario (blue diamond)

3.3 Hybrid Engine Mount

Among others, the reduction of noise transmission from the engine into the passenger compartment is a critical task for the improvement of the interior noise levels inside cars [2]. Active engine mount systems based on the above active interface in series with the existing rubber mount can be used to implement an active vibration control system at one major source of the structure-borne noise transmission. The considered passenger car has mount systems at two positions of the engine, each consisting of a rubber mount for carrying the vertical loads and a torque arm for bearing the lateral forces. In a first test, the measured force at the mount is used for feedback. As an example, results for the application of a PID controller for the realization of an integral force feedback control are shown in Fig. 8.

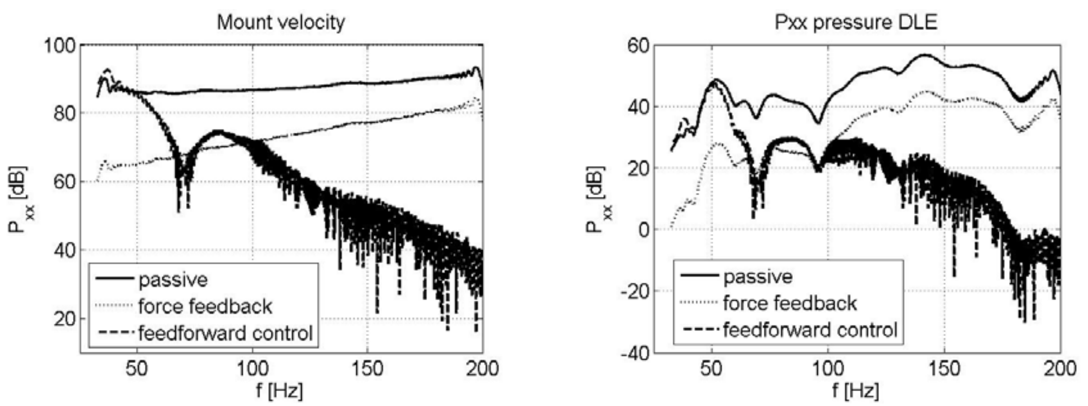

Figure 8. velocity at the mounting point (left) and sound pressure at the driver's left ear position (right)

A significant reduction of the vibration level of the car body at the engine mount position as well as a reduction of the interior noise at the microphone position can be reached. A force F of 40 N is necessary for the active hybrid mount. As a second control concept, an adaptive feed forward controller is tested. The implemented FXLMS algorithm is quite common in active noise or vibration control applications when the disturbance source is known and a suitable reference signal can be used. As an error sensor necessary for the adaptation of the control filter, the velocity at the mounting point is used. Obviously, the adaptive controller is more effective for higher frequencies, while the feedback controller reduces amplitudes at low frequencies. For the final NVH measure-

ments performed on the AVL acoustic chassis dynamometer (to enable vehicle operation under load) the following two control strategies were investigated:
- Vibration cancellation at the active engine mount,
- Reduction of interior noise based on an interior microphone feedback.

The results showed that the vibration cancellation worked efficiently on the chassis close to the engine mount but the achievable noise reduction in the vehicle interior was still low (Fig. 9). As a reason, the existence of other transfer paths is assumed. By cancellation of the input of only one path the phase relations are altered but the overall improvement is limited.

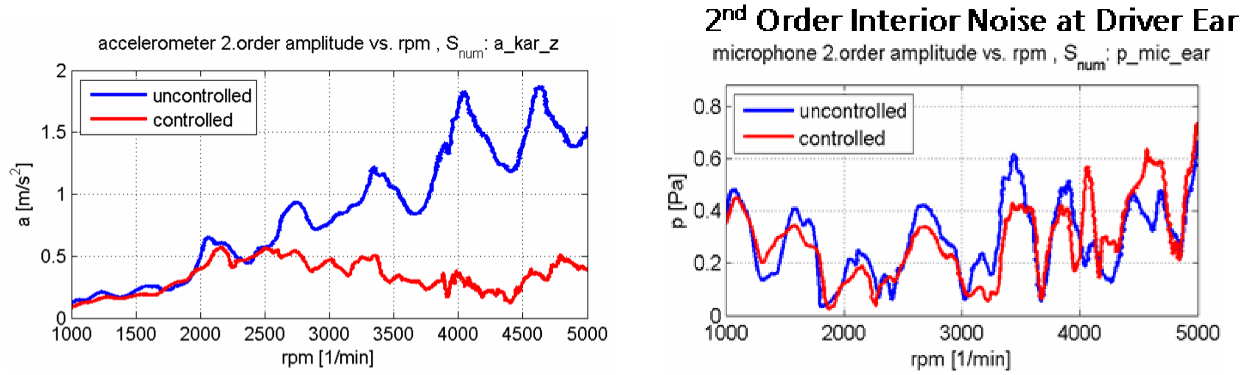

Figure 9. Experimental results

3.4 Smart Clutch for self-ventilated systems

The emitted noise of trains or locomotives in the low speed range, e.g. passage through towns, or at standstill is dominated by ventilation noise. In combination with heat exchangers, filters etc. powerful fans provide the required heat transfer or cooling of engines, converters, transformers and auxiliary units. Due to the high air flow rates these fans are strong noise sources as well. Conventional noise reduction measures such as special fans and passive silencers cannot meet the acoustic requirements. Additionally, the undiminished great demand for novel solutions is caused by the harsh operational conditions (e.g. moisture, high flow speed, vibration) and by the minimum space available.

The cooling of traction motors, see Fig. 10, by its fan is needed only in high load situations under high ambient temperatures. So, a clutch is needed that sets the fan into operation only in case the motor is on the verge of overheating – otherwise the fan stands still and, therefore, does not generate any noise. The clutch automatically engages and disengages depending on its temperature only, i.e., it does not require any additional external energy (mechanical, electrical, hydraulic etc.).

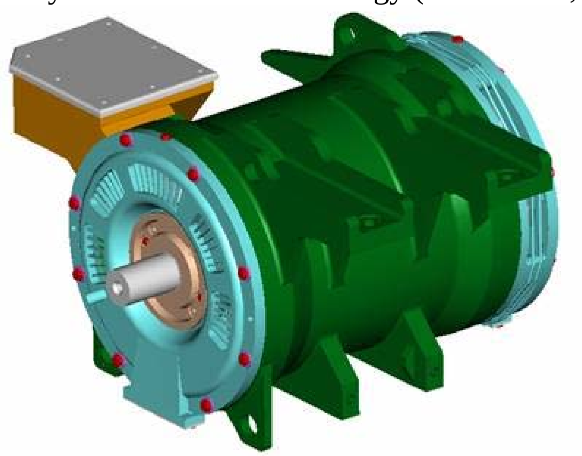

Figure 10. Traction motor with a radial fan at the rear side

The clutch system proposed and developed here is made of shape memory alloy (SMA). It comprises actuators, which change their shape when heated above a certain temperature that is characteristic for the material. In a specific design, thin wires made of SMA contract when heated up and connect a rotating disc mounted on the drive shaft with another one, to which a fan is attached, by means of a friction lining. Depending on the SMA used, the “switching temperature” can vary between 40 °C and 110 °C. If the SMA wires cool down, a compression spring elongates the wires and the rotating discs are decoupled so that the fan comes to a halt. If the wires are heated up again, the process can start over.

The clutch can be called “smart” because it does require neither an additional temperature sensor nor additional energy to engage or disengage. The SMA elements act as both sensors and actuators at the same time. Also, the clutch does not contain any liquids, which would require some sort of sealing. This leads to a simple and robust design. If the clutch is designed in such a way that it disengages instead of engages when heated up, it can be used as an overload protection device that decouples input side and output side of a rotating drive shaft.

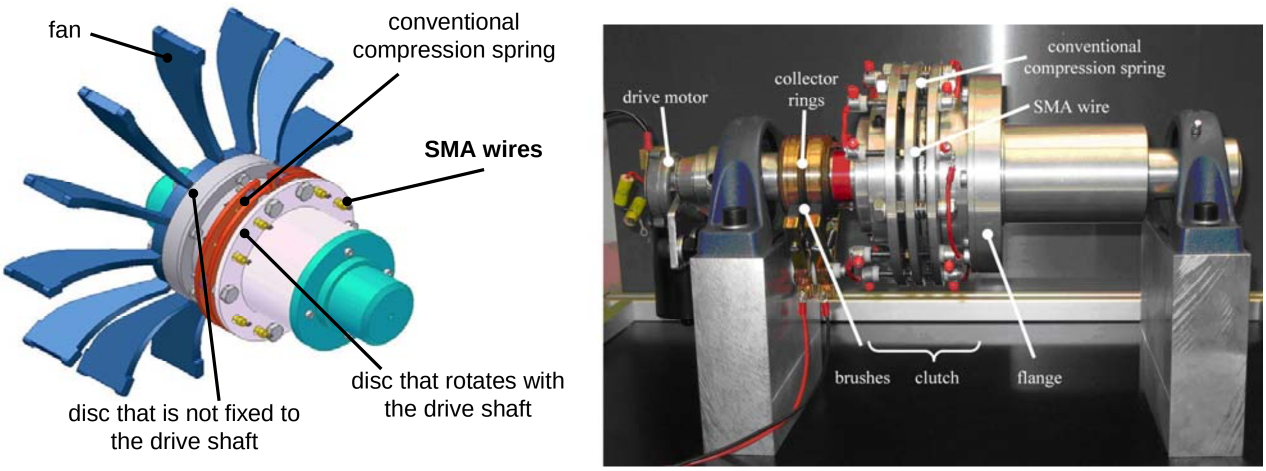

Figure. 11. CAD model (left) and demonstrator (right) of the smart clutch system

Upon specific request, electric collector rings were or can be added to the clutch that enable some electric current to be transferred into the rotating system. This way, the SMA wires can be heated up “manually” by means of the electric current. This can make sense in certain applications if it is obvious that there will be an increased cooling demand in the near future and the clutch is to engage although the original “switching temperature” is not reached yet.

3.5 Active mounts for HVAC units

HVAC units of trains comprise different noise sources such as circulation and condenser fan as well as the compressor as a vibro-acoustic and, therefore, indirect noise source. A typical representative is shown in Fig. 12, which is mounted on top of the (lightweight) roof of trams or regional trains.

The vibrations of the compressor HVAC unit mounted on the roof a tram in order to air-condition the tram driver’s cab are also a source of annoying noise levels inside the driver’s cab. Therefore, two different devices were designed to suppress the vibration transfer from the compressor to the housing of the unit. The first one is an active tuned vibration absorber that reduces the vibrations caused by the compressor, see Fig. 13.

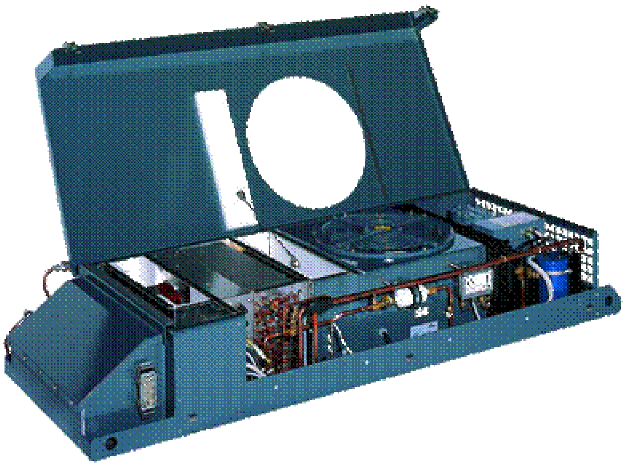

Figure 12. **HVAC unit comprising different noise sources such as circulation fan and compressor (vibration), relevant for the noise level inside the driver's cab.**

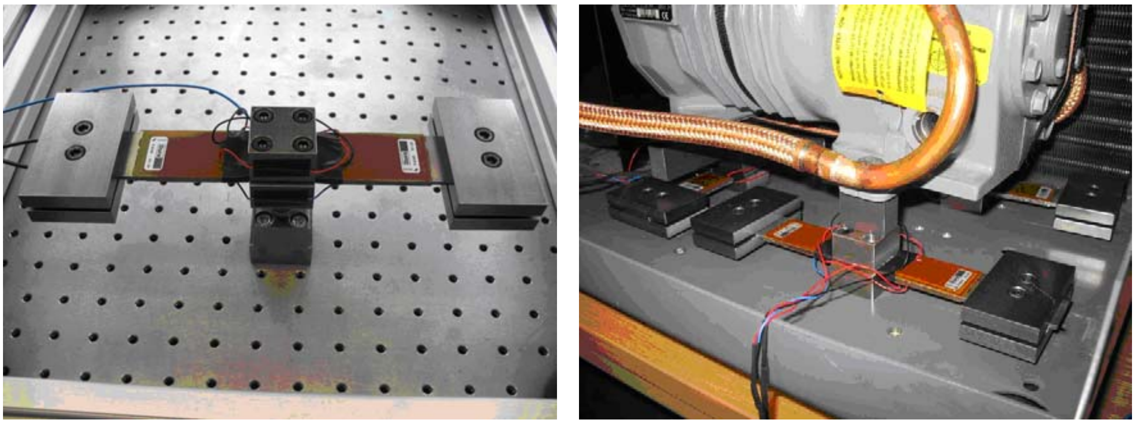

Figure 13. **Lab experiments performed on a single active tuned vibration absorber (ATVA, left) and ATVA demonstrator (right) mounted beneath the compressor.**

This vibration absorber consists of two discrete masses attached to the ends of a cantilevered beam and is tuned to 50 Hz. This fundamental frequency can be varied within a certain range by an acceleration feedback control system using the acceleration of the discrete masses as input, thus virtually adapting the mass of the absorber. In addition, the acceleration at the mounting point can be used as the input to an adaptive digital control system such that the absorber behaves as a vibration compensator at higher frequencies. The second one is an active mount based on four piezoelectric stack actuators and an elastomer part (Fig. 14) that deflects the effective direction of the piezo stack displacement by 90 degrees from the horizontal to the vertical direction while amplifying the displacement by a factor of approximately 30.

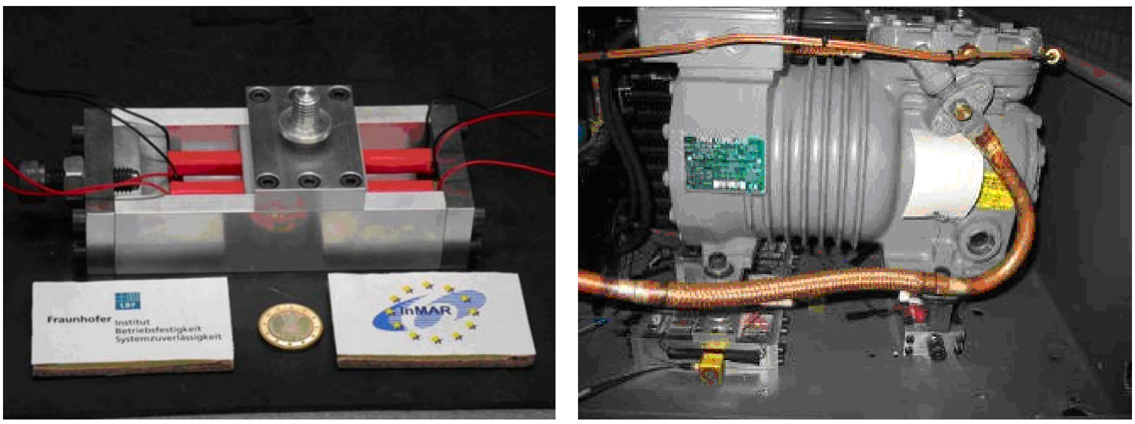

Figure 14. **Active compressor mount, prototype (left) and application beneath the compressor (right).**

These two different systems had been tested under real application conditions, i.e., mounted beneath the compressor and with the compressor running. The measurement results of the acceleration of the bottom plate of the HVAC unit showed that the vibrations could be reduced by use of feedback and feedforward control strategies up to 20 dB with the active tuned vibration absorber and respectively up to 15 dB using the active mount.

4. CONCLUSION

The focus of today's R&D projects in the automotive industry lies on the improvement of lightweight design, product quality impression, comfort and life cycle cost as well as noise emission, pollution and safety, whereas the latter are especially driven by legal requirements. This trend will continue whereas a special focus will be on exploiting the well-known multifunctional, intelligent material systems. Even though today there still are no such fully adaptronic structures within commercial vehicles, it is clear that at least most OEMs and Tier 1 suppliers – supported by R&D facilities - investigate the potential of smart structures for various applications. Most automotive R&D projects within smart structures are concerned with active vibration control (AVC) and active structural acoustic control (ASAC) for optimization of NVH (Noise, Vibration and Harshness) characteristics and even sound design.

Within this context, the 4-year Integrated Project "Intelligent Materials for Active Noise Reduction – InMAR" was funded under the 6th Framework Program of the European Commission. The research work conducted in InMAR by 41 partners lead to

- laboratory-scaled demonstrators proofing concept of ANR,
- cost-effective design tools for development of ANR systems,
- new intelligent material systems meeting automotive requirements and
- electronic hardware meeting automotive requirements.

Although significant steps towards the commercialisation of smart structures in transport related application have been achieved, further RTD effort should be spent on

- the combination of passive and active measure in a holistic noise abatement concept,
- using synergies between "smart systems", lightweight design and safety to realise a concurrent lightweight design and
- developing ANR systems to a competitive technology.

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