The Integrated Project "Intelligent Materials for Active Noise Reduction" – An overview and first results

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Introduction

During the last decade fundamental research on smart structures using intelligent materials has raised industrial interest in applying these results to many problems found in commercial and civil life. The main objective of smart structure technology is noise and vibration reduction in civil engineering, machine tools, automobiles, trains, and aerospace engineering. Both strongly coupled phenomena limit the design of highly advanced and efficient lightweight structures, whereby nowadays noise is considered one of the worst forms of environmental pollution worldwide. As stated in the EC white paper "European Transport Policy for 2010" [COM(2000)468], over 100 million people in the European Community are seriously affected by noise, causing an estimated damage of 10 – 30 billion €/year. In addition to simply being annoying, day-to-day noise exposure may cause serious health problems such as sleep disturbance, stress, disturbance of mental activities, hardness of hearing, and even deafness as well as an increased risk of heart attacks. For example, the risk of a heart attack increases by 20% at noise levels above 65 dB(A) (outdoor L_{eq}), and a child's learning ability significantly decreases with increased noise levels. Consequently, the political target of the EC must be the substantial reduction of the number of people regularly affected by long-term, average levels of noise. Taking into consideration only road and rail traffic, 32% of the population is seriously disturbed by an outdoor noise level of L_{eq} > 55 dB(A) and 13% of the population has serious health problems as the result of outdoor noise levels above 65 dB(A). But, due to increasing traffic, noise exposure in Europe by road and rail has already reached its highest levels. In Germany, for instance, inner urban traffic reaches a noise level of 81 dB(A) during the day, 72 dB(A) at night, and freight rail traffic up to 79 dB(A) at night. With a further increase in traffic, an additional elevation of up to 5 dB(A) is to be expected in noise levels. The EU is defining new standards for the year 2010 to compensate for these noise emissions, targeting a reduction of 19 dB(A) for road traffic and an even higher required reduction of 21 – 26 dB(A) for freight rail traffic. Moreover, the WHO is striving for a more ambitious reduction of up to 29 dB(A) for road traffic and up to 34 dB(A) for railways. It is obvious that the EU and WHO goals cannot be achieved with advanced traffic management or political methods (e.g. traffic restriction) alone. An approach based on lightweight design and smart structure technology combined with traffic management concepts has to be pursued. Beyond exterior noise aspects, interior noise disturbance also has to be considered, particularly for the drivers of automotives. Noise exposure within vehicles significantly contributes to the physical fatigue of the driver and, as a consequence, accounts for a significant number of accidents with fatal or serious injuries. Beyond their impact on noise, smart structure technology will for the first time allow for a concurrent lightweight design that enables the efficient use of natural resources in the product itself (less fuel consumption, less exhaust emission,…). With the future requirements fo highly efficient, emissionless lightweight structures and increased standards for any type of emission, new intelligent materials systems are needed that allow for both highly damped and controllable as well as light but durable structures for any type of high-tech application.

Presently, many intelligent materials systems such as fiber composites with embedded piezo-ceramics or shape memory alloys are derived, characterized, and applied in smart structures on a laboratory scale without having an impact yet on the design rules for engineered structures or without their application in mass products. Although their potential could be demonstrated and realized to a certain extent in prototype structures, the performance of intelligent material systems is still insufficient. They require an unacceptable electronic periphery, data on their durability and reliability is lacking and, most importantly, are not yet included in standard design and manufacturing processes. These deficits should be overcame by the Integrated Project "Intelligent Materials for Active Noise Reduction - InMAR". The overall objective of InMAR is the research and realization of intelligent, high-performance, adaptive material systems with integrated electronics for different individual applications. These are applicable for noise mitigation purposes - even in highly loaded structures as construction material - in the same manner as common passive or lightweight materials have been used up to now. Aside from the development of the materials or material systems themselves, this research also includes their characterization, simulation tools for the design process, handling and manufacturing techniques as well as the reliability of these material systems. According to common trends in engineering, the development has to be performed on an experimental as well as theoretical and numerical level.

Since the requirements for intelligent material systems - in contrast to those for conventional lightweight materials - greatly depend on the intended application and operational conditions, these material systems can only be developed in a concurrent approach that simultaneously considers the application. From manifold application possibilities, noise problems in land-based traffic and related infrastructure such as buildings, bridges and tunnels are chosen for application purposes. The newly designed intelligent material systems will be applied to active noise reduction concepts based on Active Structural Acoustic Control (ASAC) or Active Noise Control (ANC) for Sound Quality Design. It is expected that for automotives, trains, and in civil engineering reduced noise radiation and emission will increasingly become more of a design aspect which cannot be achieved by conventional materials and concepts. In a broader perspective, advanced intelligent material systems can be introduced to noise and vibration-related design aspects in all fields of industrial and civil applications.

The IP InMAR has a duration of 4 years and a total budget of 27 Mio. € of which almost 50% is provided by the industry.

Scientific and Technological Objectives of InMAR

Since research on intelligent materials, control strategies for active noise reduction and the simulation of both is highly interdisciplinary and each subject is highly dependent on the other, the fundamental research on these subjects has always been considered together with the technological development of active noise reduction systems. Technology development will be performed exemplarily for applications in automotives, trains and infrastructure. As underlying principle for noise reduction concepts, Active Structural Acoustic Control (ASAC) will primarily be considered. Since the noise radiation will be controlled either by controlling the structural vibration of the radiating structure or by interrupting the structure borne sound path, special focus has to be given to intelligent material systems as construction material. However, especially when dealing with internal noise problems the Active Noise Control with new acoustic actuators and materials, possibly combined with the ASAC approach, may prove to be more feasible, and will also be studied here.

Research on intelligent material systems addresses the design of intelligent materials, the embedding of electronics and the design of control strategies for broadband noise. For a technological breakthrough of active noise reduction, the sensing and actuation capabilities as well as the load-carrying characteristics of intelligent materials, defined as composites consisting of transducer materials and conventional materials, have to be enhanced. These intelligent materials, together with the necessary power electronics, electronics for data management and the control, form a system where the individual components interact in a complex manner. The electronics can either be embedded in the composite or be stand-alone in a miniaturized form. When designing the structure of the intelligent material and the control strategy the highly stochastic, broadband excitation of noise has to be taken into account. Although major research work has already been carried out, aspects such as characterization, handling, manufacturing, reliability and recycling were not addressed so far. Research on intelligent material systems includes the numerical as well as the experimental simulation. According to the different research aspects on intelligent material systems, the fundamental research is divided into the three technology areas: Intelligent Material Systems, System Integration and Life-Cycle of these materials and systems. The trisection also reflects the evolutionary progress in the development of intelligent material systems. Within these technology areas intelligent material systems will be designed and characterized, simulation and manufacturing technologies developed according to the problems defined in the application scenarios.

In order to bring advances in intelligent materials to the level of industrial use in integrated applications, the material design process has to become part of the complete product creation process. This demands that the product's functional performance and respective simulation models, which are the cornerstone of today's design process, be capable of supporting the specific aspects related to advanced materials, active systems, actuators, sensors, and control, and that these be integrated into system-level and virtual prototype models. An essential requirement for this is the coupling of various physical disciplines such as structural mechanics, acoustics, electro-magnetism, or durability with control algorithms within one simulation. Moreover, effects on a very different scale need to be interconnected, ranging from the microstructure of the active materials to the acoustic far-field enclosing the structure under consideration, which, in turn, will be the controlling variable for the intelligent material. This level of bi-directional integration is not known in other engineering disciplines and requires a new class of models and tools. Finally, proper parameterization, a reduction of the applicable models, and the fast recalculation of various design alternatives will be key elements in deriving an optimal system and material design. Such a modeling approach will be established in the *InMAR* project. Based on this approach, the simulation of full-system behavior can be performed, taking into account the characteristics of the innovative material as well as multi-attribute performance goals. This then allows for the proper target setting on the level of the materials and material systems (essential for "materials by design") as well as for the development of optimization procedures for the material parameters and material system configuration.

The biggest achievements in weight reduction, size reduction and probably cost reduction are obtained when all functional components are fully integrated. Even stronger, it is unlikely that such systems will be introduced if they are not fully integrated. In order to realize these objectives, some of the components could be given multiple functions, such as thin active layers which are used for mounting the electronic components, for the interconnections, and for example the face layers in sandwich constructions. The design of such systems should be done in an interdisciplinary manner and with constraints given by the industrial partners. The design of the system is complicated by the fact that the control of multichannel systems for broadband noise reductions is computationally rather demanding, and usually requires heavy signal processing hardware because fully programmable systems such as a Personal Computer or Digital Signal Processor are used. So reduction of computational complexity and hardware implementation of certain parts of the algorithm have a direct influence on the possibility to achieve the desired goals and should be taken into account in the overall design process. Additionally, at relatively high sound pressure levels and vibration levels, also the weight and size of the power amplifiers should be reduced. The combination of detailed simulation models is needed to optimize overall system performance. However, from a practical point of view ,the availability of simpler design rules is important. These simple design rules can be on the component level but also at a subsystem level or even system level.

The main objectives of the technology areas are to understand, to design and to develop:

- new complex multifunctional passive, semi-active and active materials and material structures,
- actuator and sensor systems based on the developed materials, fully operational under harsh environment, high and broad-band load and under large deformation
- their manufacturing technologies,

and

- novel, miniaturized control and electronic systems for multifunctional materials, and for actuator and sensor systems
- simulation and optimization tools for the design of intelligent systems
- technologies to integrate intelligent material systems in structural components and
- methods and procedures to assess their reliability, environmental impact and life-cycle including condition monitoring

to be used in the macro-scale application of active noise reduction. The expected innovations on intelligent material systems in total will increase the acceptance of smart structure technology and the industrial applications in order to replace classical, ineffective methods of noise and vibration suppression.

Beside the fact that the automotive industry is a driving factor in the economy, automotives are to be considered as one of the major contributor to noise emission. Beyond the aspect of exterior noise, major effort is undertaken to improve or design the interior noise of automotives. Most concepts are based on absorption and state a contradiction to light weight design. Therefore, automotives are an ideal application for active noise reduction concepts. The major noise sources of automotives or trains are power train and rolling noise and are consequently considered here. In the overall view of the vehicle, any kind of attenuation (rolling noise, engine, aerodynamics, etc.) of the vehicle body (not only body-in-white) and their effect on radiated noise to the exterior as well as to the interior has to be investigated. Depending on the attenuation, structural borne sound within the body or the vibration of panel-like components such as sheet metal panels or windows has to be controlled for an efficient noise reduction. All problems have in common the need for advanced concepts for active noise reduction based on intelligent materials. Current state-of-the-art based on passive approaches are insufficient to meet the future requirements. The objective will be the development of advanced noise reduction systems requiring high-temperature, highly flexible, highly loaded or transparent intelligent material systems.

The train industry is facing similar problems. The major noise source of trains is the rolling noise. Having in mind that the system wheel-axis-bogie is a high-loaded structure and highly damped, intelligent materials must be developed to reduce the radiated noise of wheels. Those highly damped materials may function with no external energy, by generating their own energy or with distributed but independently working units with actuators and sensors. Since ANC or ASAC concepts based on intelligent materials are only demonstrated for low-loaded structures, the design of an intelligent material system for high-loaded structures will state a major breakthrough in this technology. Beside the rolling noise, aerodynamically induced noise should be considered. In particular high-speed trains are emitting noise from the aerodynamically excited large, almost flat side panels of the wagon. These panels will contribute even more to the overall radiated noise of trains when passive and active noise optimized wheels are used. Smart panels with embedded actuators, sensors and electronics will be developed. Furthermore, the ventilation systems of trains significantly contribute to the noise radiation when the train is in the station. Facing similar requirements, research results obtained on train ventilation systems can easily be adopted for automotives and buildings.

Research performed on infrastructure such as buildings or bridges has to been seen in context with an overall reduction of noise affection for the population. Although within this Integrated Project concepts are being considered to reduce the noise at the source, a significant noise level will remain to affect people. Particularly for buildings at inner urban roads or close to rails or airports the remaining noise level will still exceed the tolerable limits for people. Therefore, as an accompanying measure the transmitted noise through windows and facades should actively be controlled. Discussing active windows and facades it is important to keep in mind, that for the well-being of the people not a total noise reduction but a frequency selective reduction is required. The sound of birds, for instance, should still be heard. Within buildings, interior noise and sound quality is also determined by heat, ventilation, air condition systems (HVAC) and elevators becoming even more significant, when the noise emission from outside is controlled. Again active concepts based on intelligent materials will be developed applicable in the state-of-the-art civil engineering technology. Bridges and tunnels are important noise and vibration sources generated mainly by railway and highway traffic. The negative impact of this noise pollution and these vibrations on the environment is usually increased by the proximity of bridges and tunnels towards urban areas. Passive solutions for noise and vibration mitigation have demonstrated a good efficiency but the performance of such solutions shows some limitations.

Noise reduction in all above fields can find great benefits from new intelligent material systems, new components and devices and new noise control systems as derived in the technology areas. Of course, the cost aspects are quite relevant when the balance benefit/cost is taken into account to decide whether a technical solution is ready for production. Besides, also innovative simulation tools can help to better understand phenomena and problems, so that new applications of existing technologies or technologies derived are envisaged. The main objectives of the application scenarios are to design and develop advanced active noise reduction concepts for

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

as cost-effective solutions for a broad-band noise reduction up to 10 db(A) or higher for exterior and interior noise.

Project Structure

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 target markets by providing S&T excellence and by ensuring the quality of the consortium.

Industry		**SME's**	
Volkswagen	GER	ERAS	GER
Ford	GER	IGAM	GER
Dornier	GER	Smart Material	GER
Siemens Trans.	GER	Panphonics	FIN
FEV	GER	Micromega	B
LMS Int.	B	D2S Int.	B
AVL	A	Techno First	F
Rieter Automot.	CH	IMMG	GR
Schindler	CH		
Saint-Gobain	F		
Renault	F		
Volvo	S		
Bombardier	S		
Lucchini	I		
RTD		**University**	
Fraunhofer Ges.	GER	HSU-HH	GER
DLR	GER	TU Darmstadt	
TNO	NL	ULB	GER
VTT	FIN	KUL	B
CIRA	I	KTH	B
C.R.F.	I	ISVR	S
INASMET	E	UTW	UK
EMPA	CH	TU Delft	NL
		CNAM	NL
		TU Mailand	F
		BUTE	I
			H

Table 1 InMAR Consortium

The scientific and technological objectives are reflected in the structure of the IP as shown in Figure 1 below. According to these objectives, the IP *InMAR* is structured in three complementary technology areas (subprojects) 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.

First Results

The IP InMAR started January 2004 whereas all subprojects and their respective work areas have started with the application of state-of-the-art technology. The starting point of the work in both the Technology Areas and Application Scenarios was the experience taken from previous European or national projects and the pre-existing know-how provided by individual partners. The general objectives in the beginning were to develop basic technology that is crucial for the success of the application scenarios and to develop concepts for the NVH problems under consideration. Within the first 18 months these NVH problems have to be described and the targets defined.

The technology development in the application scenarios has started with state-of-the-art technology and with applying surrogate active elements that represent the elements to be delivered by the technology area later on. This is a concept stage in a designated surrounding of the respective application scenario. These activities are aimed at determining the requirements (specifications) for the technology area. At the same time, the technology areas have begun with the work of designing and developing the intelligent material systems, the actuators and sensors, as well as the integration techniques and test methods. Focus is on piezoelectric- and SMA-based material and actuator and sensor systems with extended performance such as high temperature or tranparency. The new developments will be adopted and their availability tested by the application scenarios. Since the specifications from the application scenarios obtained by the baseline analyis are presumably very challenging with respect to operational loads, frequency range, and environmental condition, the risk that these requirements cannot be met by the considered material systems is very high. Therefore, a first gateway has been defined by evaluating the system approaches and the defined specifications which is currently under progress.

So far, research has focussed on the feasibility of concepts and the definition of requirements and specifications. A significant progress towards the identification of the underlying NVH problems and their requirements has been achieved. In all application scenarios, the components of the vehicle or structure has been identified and measurements as well as simulations performed leading to substantial knowledge of the underlying NVH problem. For the actual measurements and simulations, hardware in form of vehicles or components and their numerical models has been provided. Based on these results, concepts for active systems can be derived in the following project year.

In the technology areas application-oriented research as well as fundamental work has been performed. The application-orientated research strictly focuses on the needs of the application scenarios and are performed together with the application scenarios. In close cooperation with the AS, research has been focused on development of strategies and methologies how on to meet the requirements of problems identified in the AS cluster. Furthermore, tools and concepts have been adopted allowing the AS to develop their ANR system. Regarding the more fundamental oriented research, feasibility studies were mostly performed starting by screening the state-of-the-art followed by simulations.

In the following, a few selected results of 3 work areas will be presented.

Selected results

Reliability of Active Systems

Today, not only technical pros and cons and underlying R&D efforts and costs are taken into consideration when assessing the success of modern technical systems and products as well as that of new technologies for product optimization, but also the economical aspects which have obtained a fundamental significance. Among these aspects, the long-term accruing costs are gaining in importance in addition to the development and acquisition costs that occur at the beginning of a product's life cycle. The significance of LifeCycle Engineering (LCE) will continue to increase in the future. An essential part of the lifecycle costs result from reliability, maintainability, and availability, recycling and environmental compatibility. As essential part of every development of a new technology, *InMAR* further included the analysis of the general conditions and governmental regulations, the evaluation of the technical and economical compatibility of active systems to these conditions and regulations, as well as the derivation of recommendations for the conception, design, operation, and development of new material systems.

With respect to the complex, controlled and non-controlled, active systems, appropriate methods and procedures still need to be developed for the experimental simulation of characteristic 'external' operational loads while taking into consideration their interactions with the host structure. Component degradation and failures as well as system failures have also to be considered whereby new methods and procedures. for the experimental simulation as well as for the numerical assessment of the system reliability are needed.

In the beginning, emphasis has been placed on the cycling experiments of vibrating beams. At first, a static and dynamic modelling of the beam system was performed. Based on that, cycling experiments were carried out at elevated temperature (75°C) at the 2nd bending resonance frequency (approx. 125 Hz). It has been found that at 150 x 10^6 cycles the static electromechanical response of the beam decreased by approx. 18%, resulting in a lower strain amplitude after cycling (Fig. 2). In order to find obvious damages, optical images were taken from the surface of the samples. However, no visible damages were found, and it was concluded that the damage occurs on a meso- or microscopic scale (Fig. 3).

Noise Reduction by Brakes

The WA "Tires and Breaks" deals with tire / road interaction as the main source of noise of automobiles at higher speeds. With respect to the work tasks on breaks, the brake system BOSCH BENDIX V with floating calliper and not-ventilated brake disc was chosen as target system for in-depth investigation (Fig. 4). With this system four major work tasks have been carried out dealing with the simulation of the active system, the actuator concepts, modelling of the passive brake system and first experimental investigations.

In order to model the active system in closed loop it was necessary to model the Brake System. Therefore an NVH FE model of the Bosch Bendix V brake system has been created. This baseline model has been meshed and assembled appropriately in order to simulate the real mechanism of the brake. It consists of about 25000 grids in order to be of sufficient complexity to enable frequencies up to 15 kHz to be detected and analysed. The model will be the base for the numerical – experimental comparison as well as the baseline for the simulation of self–excitation mechanism. This model has been already tested and validated with respect to the functional specification of the brake. Based on this model, the underlying brake squealing problem including the self excitation mechanism has been assessed. In future work, the NVH-Model has to be reduced in its complexity in order to perform simulation in the MATLAB/SIMULINK environment of the active system to be developed.

Noise Reduction by Ventilation Systems

The aim of the work area "Ventilation" is to overcome the lack of alternatives and is initiated and supported by novel, suitable materials which are robust, reliable, durable, and intelligent. Their configuration within active control strategies for several application scenarios on railway vehicles, e.g. thermal, load-controlled fans of self-ventilated traction motors and activated, acoustic resonance structures, will complete the radical innovation. Due to the common features and noise problems of HVAC systems of trains and cars, special efforts will focus on the generalized and multi-sectoral applicability of the developed materials and noise-control solutions.

At first, typical noisy ventilation components have been selected comprising a self-ventilated traction motor (Fig. 5) and a driver cab HVAC unit (Fig. 7). These components are installed in suitable acoustic laboratories, such as semi-anechoic chamber and aerodynamic/aero-acoustic wind tunnel and baseline measurements performed. The diagnosis of noise sources and propagation paths, of operating conditions and restrictions is required for the aero- and vibro-acoustic modelling and for additional acquisition of special experimental data.

The acoustic treatment of the self-ventilated traction motor strongly depends on thermal (load characteristics), aerodynamic (performance) and mechanical (torque transmission) aspects. As the air outlet is the dominating noise source an improved aero-acoustic design of fan and flow paths (active, passive, hybrid methods) as well as a temperature controlled viscoelastic (de)coupling of the fan with a smart clutch will be required (Fig. 6). Furthermore, modifications of the aerodynamic and acoustic fan performance needs to include active blade shaping and/or positioning system and adaptive control systems for separate tailored fans.

The HVAC unit for driver's cab includes three different (independent) sound sources (condenser fan, ventilation fan, compressor) with different characteristics and propagation paths. Additionally, interior and exterior immission points are involved. Since there is significant (and annoying) tonality of the flow noise (Fig. 8), e.g. ventilation fan noise, specific tailored active material systems are considered. In order to reduce noise level and tonality actively absorptive silencers or activated acoustic resonators have to be developed or adapted to the scenarios which were found during the base line analysis.

Contact / Further Information

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Acknowledgement

The IP InMAR is funded by the EC under the contract NMP2-CT-2003-501084. The author wishes to thank all InMAR partners for their contribution.

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
				Elevators

Figure 1 Project structure

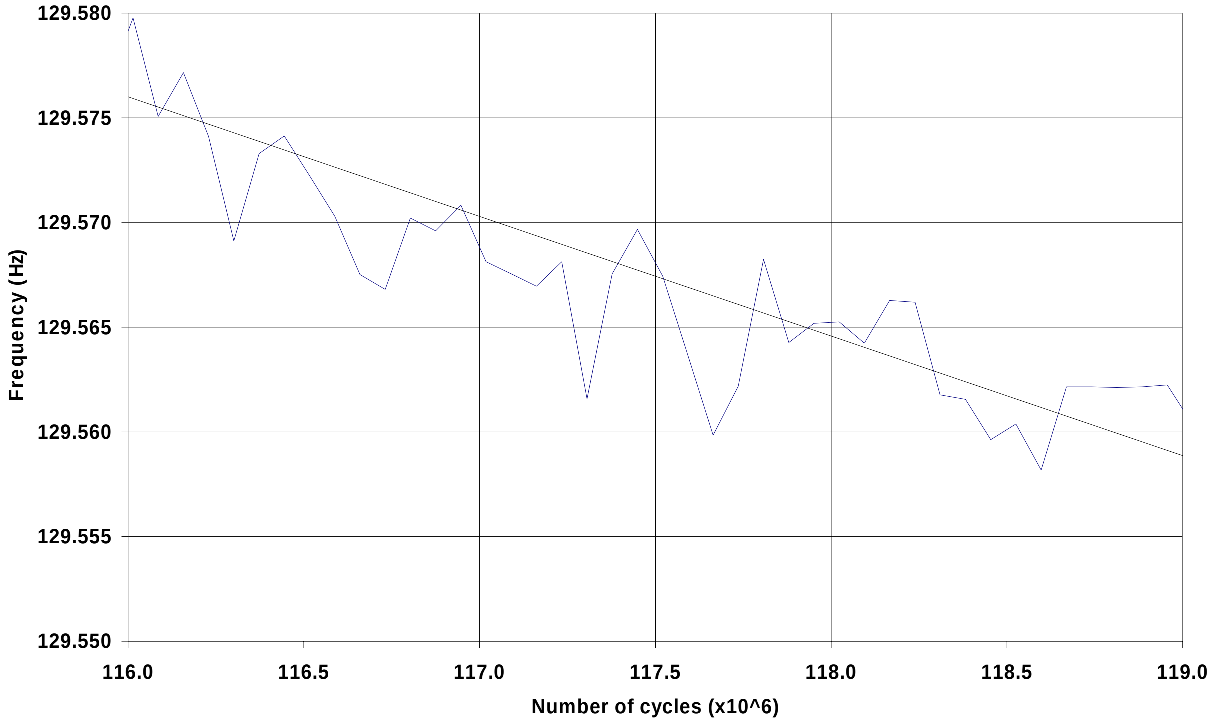

Figure 2 Degradation of cycled active beams (Source: IMMG)

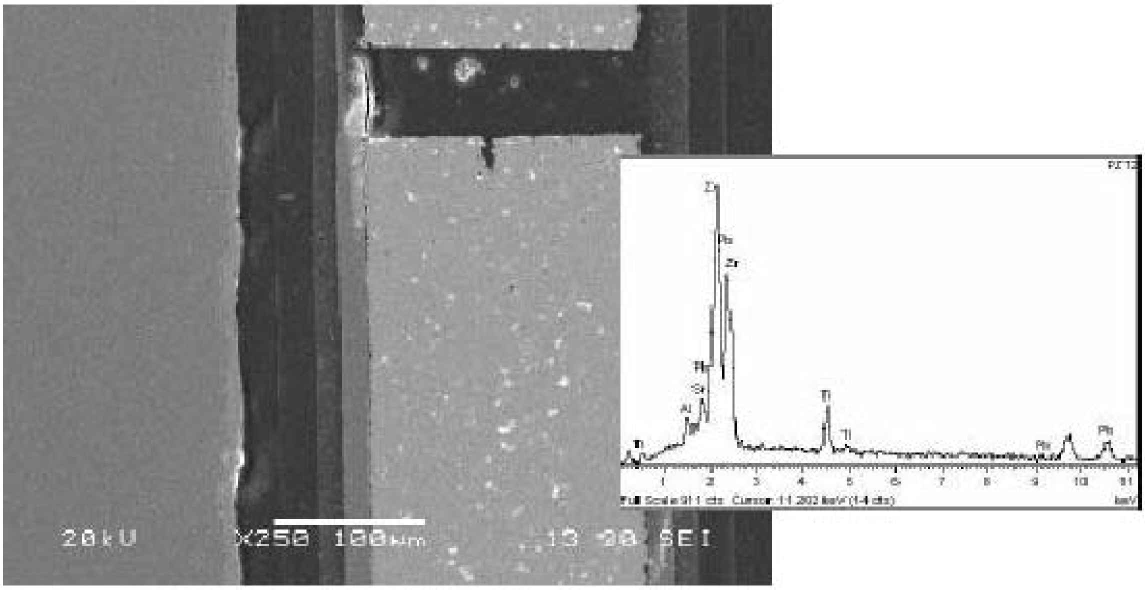

Figure 3 Microstructure of a damaged cycled active beam (Source: INASMET)

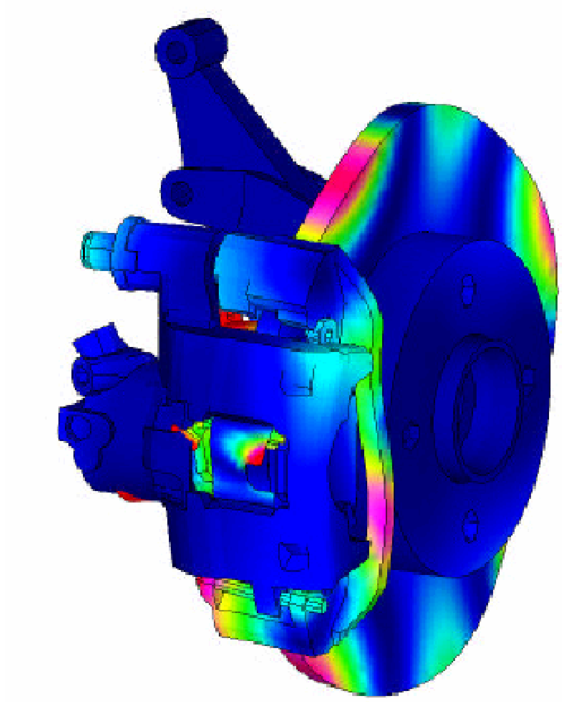

Figure 4   Bosch Bendix V – most critical eigenmode at 3.3 kHz (Source: C.R.F.)

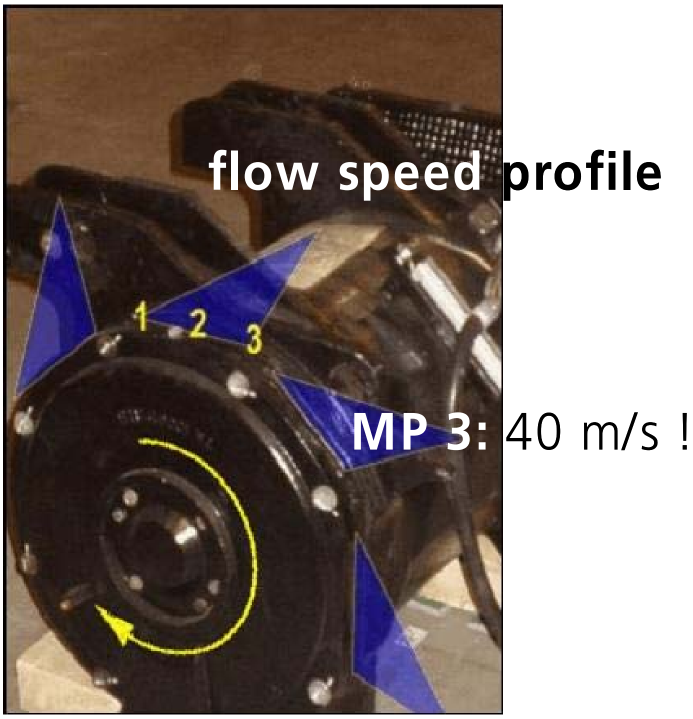

Figure 5   Considered traction motor (Source: Siemens, IBP)

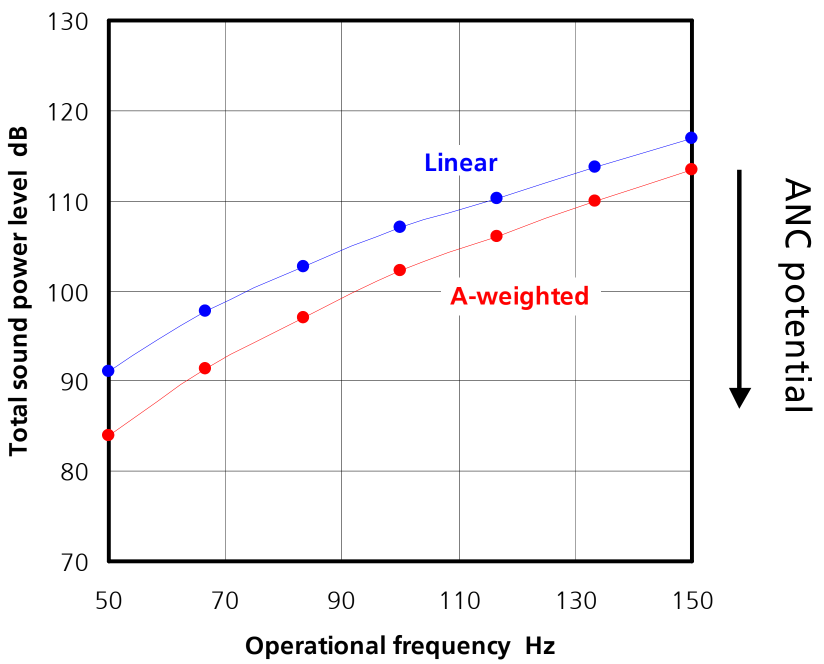

Figure 6 Potential of ANC measures (Source: IBP)

Figure 7 HVAC unit (Source: Bombardier)

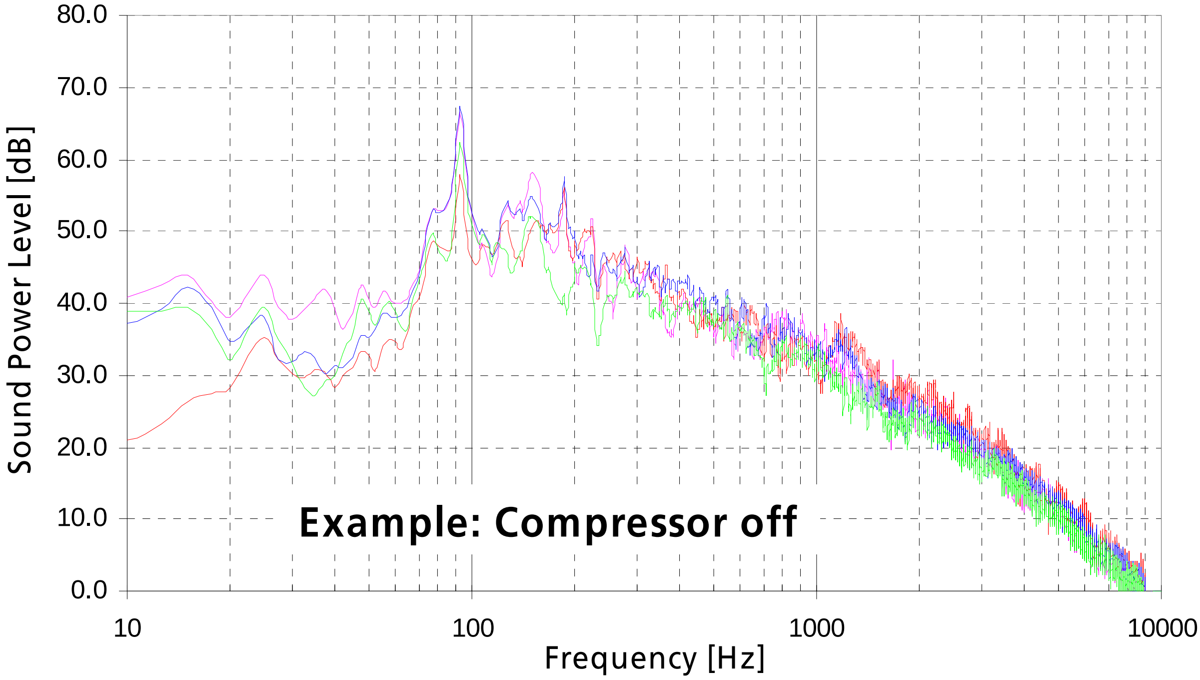

Figure 8 Tonal noise radiation of HVAC unit (Source: CRF, IBP)