PROJECT PUBLISHABLE SUMMARY

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .
[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

1. Executive Summary

Improvement of vehicle noise and vibration without affecting other performances is proving to be extremely difficult if not impossible with state-of-the-art technology. Frequently, new technologies in the fields of smart materials and active control provide potential solutions but have only been proved in the laboratory. Thus, exploiting the potential of integrated solutions for the control of noise and vibration in vehicles to improve vehicle fuel efficiency and reduce their impact on the environment is the principal motivation behind the *Green City Car* project. The overall aim is to integrate advanced laboratory-level technologies with conventional solutions with direct application to next generation city-cars.

Today engine downsizing represents the most direct and cost effective approach to improving fuel efficiency in city cars in order to ensure significant reductions on the impact on the environment while still providing acceptable levels of performance and vehicle 'fun-to-drive'. However this new generation of engines, while being ideally suited to city vehicle applications, can result in a perceivable degree of deterioration in terms of noise and vibration when compared with the vehicles currently on the market. Similarly, the mass reduction required to lower CO_2 emission and fuel consumption can lead to considerable augmented noise levels, which should be adequately compensated by integrated, light noise abatement means.

Pursuing the different passive and active concepts in a holistic approach, *Green City Car* demonstrates the feasibility of applying active systems to NVH-related problems light city cars from a system point-of-view. During the project, an existing city car equipped with a twin-cylinder engine has been considered. The vehicle is equipped with the latest technology in terms of safety aspects related to pedestrian's impact and car-to-car compatibility, which are of major importance in an urban environment. The noise reduction technology developed and implemented in this city car addressed the mass reduction of the complete sound packages, the application of new materials, passive or active piezo-electric or electro-magnetic patches on vehicle and engine panels, smart Helmholtz resonators and broadband active noise cancellation. A complete integration and correct balance of such components should be found out, in order to achieve the given objectives of noise and weight reduction.

Following main results has been achieved within Green City Car:

- Set of validated stroke-amplified actuators
- 19% weight reduction on the existing sound package
- a new design for tires giving a good compromise between low resistance and low noise
- validated active engine mount for the F 500
- assessment of noise sources intensity of a city car
- validation of feed-forward active engine noise controller
- 6-10 dB for idle conditions and more than 20 dB for a run-up at the entrance of the intake system by an active Helmholtz resonator
- a prototype of the wireless sensor system for engine components
- significant control of the first engine order of around 10 dB is achievable from around 1500 to 6000 rpm by cabin active noise control
- reduction in engine noise of up to 7 dB(A) has been detected at front passengers' ears during an engine run-up in third gear with the adapted car

2. Project context and objectives

Today's cars represent a complex compromise between contradictory requirements with regard to safety, exhaust emissions, noise, performance and price. In this context, is widely recognized that the quality of life, particularly in the urban environment, is heavily influenced by air and noise pollution resulting from road traffic. Thus, one of the top priorities for car manufacturers is the reduction of noise and emissions from vehicles, with particular attention currently being focused on CO_2.

Within a vehicle many components contribute to the overall emitted noise of a vehicle individually radiating noise between 60 – 70 dB(A) (see Fig. 1). Having different dominant noise sources of the same order (e.g. within 4 dB(A)), the treatment of only one sources will not affect the overall radiated noise. Contrariwise, a previously masked noise source could become dominant being more annoying than the treated noise source. In order to achieve an overall noise reduction for vehicles, all noise sources and their transfer paths to radiating components have to be treated simultaneously and in a holistic approach. The problem of multiple noise sources and transfer paths will become more and more challenging with the upcoming, lightweight driven multi-material design of the vehicle body and envisioned flexibility and modularity of the vehicle power train. The dominant sources and their quality (e.g. frequency content) will vary from car to car as well additional transfer paths will occur.

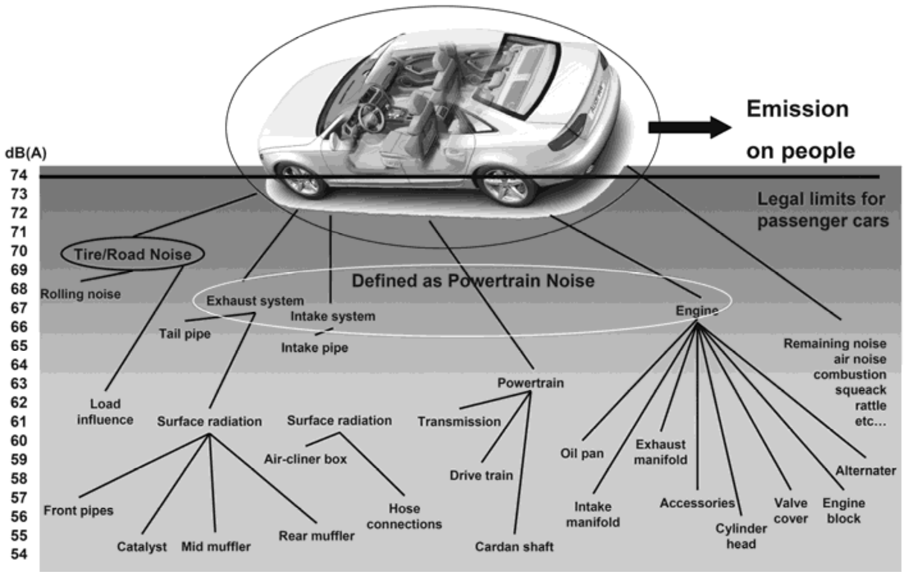


Figure 1: Components with Influence on Noise (Source: Porsche)

The scope of *Green City Car* is therefore to develop flexible, integrated passive and active solutions which will not only permit noise and vibration to be attenuated in new vehicles equipped with the next generation of highly fuel-efficient power trains but enable vehicle design guidelines to be defined in order to reduce weight without compromising on comfort and safety. On the basis of this application, the project poses a series of specific technical objectives, the fulfilment of which will be demonstrated using a 2-cyclinder IC vehicle which includes:

- Definition of design guidelines for reducing vehicle weight by adopting integrated solutions for noise and vibration attenuation. Results will include lightweight passive noise and vibration control solutions and design rules for lightweight vehicles incorporating integrated noise and vibration control.
- Development of advanced, integrated solutions for noise and vibration control of vehicles equipped with energy efficient power trains; the aim is to demonstrate that nominally one solution, appropriately tuned, can be used to control the noise and vibration in vehicles which may be equipped with a range of different propulsion systems.

- Analysis of comparative cost benefit of developed approaches for integrated noise and vibration control with respect to the conventional approach to vehicle design for acceptable vibro-acoustic performance; Deliverables will include a business case study, analysing the cost-benefit potential of the solutions developed and identifying the lead markets which will enable significant market penetration over the medium-term (3-5 years).

Improving vehicle noise and vibrations without affecting other performances has been proven to be extremely difficult if not impossible with state-of-the-art technology. Recent technologies in the fields of smart materials and active control provide potential solutions but have only been proved in the laboratory. One of the reference projects in this field is the European Integrated Project "Intelligent Materials for Active Noise Reduction – InMAR" (NMP2-CT-2003-501084). Finished April 2008, InMAR has dealt with active measures to control noise and vibrations of different sources within an automotive. Within this project, a significant noise reduction could be obtained on laboratory scale but tested on the vehicle, no significant reduction on noise levels could be measured. Main reason is the complex excitation in a car resulting in complex operational vibration modes as well as multiple vibration transfer paths. Therefore, the aim of *Green City Car* is the integration of such advanced laboratory-level technologies into conventional solutions with direct application to next generation city-car in order to assess practical feasibility, promote industrial development and determine cost-benefit evaluations.

Scientific and technical objectives

The current vehicles have already a structure optimised to have low weight without reducing the required performances. However, there are some components of the structure that can be further reduced in weight still matching the resistance, crash and fatigue performances, but giving a poor performance in terms of noise and vibrations and increasing both the structure-borne and airborne sound transmission.

In some of these components the problem is related to low-frequency resonances caused by their weight reduction. Within *Green City Car* shunted piezoelectric patches and electro-magnetic actuation tuned at the frequency of interest are considered to control these low-frequency resonances. Low-frequency resonances are also important for the acoustic cavity inside the passenger compartment. A classical solution for the pressure modes is the Helmholtz resonator, but they require big air volumes to be effective in the cabin while the space available in a vehicle is usually too small. In *Green City Car* smart Helmholtz resonators are developed using a flexible wall and shunted or controlled piezoelectric patches to reduce the required volume of the resonator without affecting his effectiveness in the noise reduction. A second issue considered in *Green City Car* is the low-frequency broadband noise: this is the case of the rolling noise (structure-borne) coming from the tyre-road interaction. A possible solution is the development of dedicated active noise control systems for the control of broadband rolling noise using a control system that reduce the noise inside the cabin acting both with internal loudspeakers or piezoelectric actuators on the suspension brackets themselves.

Another important topic addressed by *Green City Car* is damping materials and acoustic treatments which represent an important part of the whole vehicle weight. The use of damped steel panels (sandwich with steel and viscoelastic stratus) may help the weight reduction avoiding the application of the current common bitumen damping patches. Also, the use of alternative damping materials (like sprayable damping treatments with an optimised distribution over the panel surface) could help the weight reduction. For the acoustic treatments it is possible to develop innovative solutions for both the insulation of the noise sources and the absorption inside the cabin. Also, the use of composite materials or lightweight alloys on some components (like the suspension brackets) has to be analysed for his potential weight reduction.

Besides, new generations of compact lightweight two- or three cylinder IC engine structures are considered in *Green City Car* featuring many undamped thin-walled covers and panels exhibiting high vibration levels in a broad frequency range. For those, dissipation of vibratory energy in the form of structural damping using smart materials, more specifically damping by shunted piezo-electric patches, would be an appropriate solution. On the vehicle body side, the existing engines mounts have to be adapted to compensate for the excitation of the body in a broad frequency range by lightweight engines. Hybrid engine mounts are developed in *Green City Car* combining high performing elastomer materials for higher frequencies (> 500 Hz) with smart materials (such as piezoelectric ceramics) actively controlling the lower frequency range (50 – 500 Hz). Such a hybrid engine mount will be able to interrupt transfer path of the excitations coming from the engine in a frequency range as low as 50 Hz up to 2 kHz. For both approaches the source transfer paths needs to be understood in detail.

Finally, tyres are another important acoustic source for exterior and interior noise, being at the same time a fundamental component to work on for the reduction of rolling resistance. A design approach is being developed and implemented, in order to reduce acoustic emission of low resistance tyres, maybe by releasing handling performance without compromising safety.

Pursuing the different concept in a holistic approach, *Green City Car* aims to demonstrate the feasibility of applying active systems to NVH-related problems of advanced power trains from a system point-of-view. This holistic approach should lead to a reduction in noise and vibrations levels in the order of 10 dB(A) and more measurable in the city car provided (not on component level). The overall objectives of *Green City Car* are summarised as follows:

- Development of an holistic approach of noise and vibration control for city cars
- Validation of the feasibility of an integrated noise & vibration control on vehicle level having
  - same interior noise, possibly reduced exterior noise with significant weight reduction and improved fuel consumption as compared to the state-of-the-art vehicle
  - costs potentially competitive with conventional solutions
  - Development of an integrated noise & vibration control on vehicle level resulting in 10 dB(A) less noise and vibrations levels at same weight and energy consumption
  - Increasing modularity of integrated noise & vibration control
  - Increasing acceptance of city cars with energy efficient power trains from comfort point of view

3. Main S&T results/foregrounds

Active Helmholtz Resonator

The work focused on the development and implementation of the concept of an actively controlled Helmholtz resonator for reduction of the noise from the intake system of an engine. The work was structured in four parts. In WP 2 the concept of the active Helmholtz resonator was demonstrated in a simplified experimental setup. A simple set-up was created allowing for testing an active Helmholtz resonator. For this a loudspeaker (primary source representing the engine) is coupled to a tube representing the intake system. At about 40 cm from the end of the tube the resonator is coupled to the tube. The resonator is designed allowing for changing the volume of the resonator. A simple loudspeaker element is coupled at the backside of the resonator (see Figure 2).

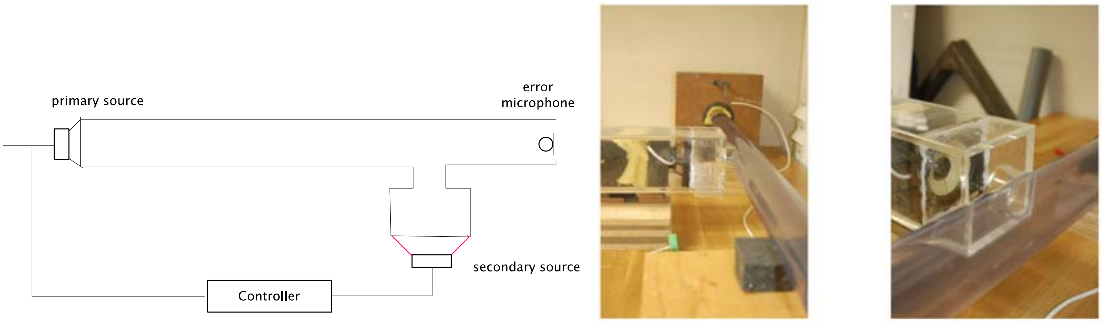


Figure 2: Sketch of the experimental setup for the test for an active Helmholtz resonator

A feed-forward control system was implemented. The results showed the functioning and robustness of the approach. Figure 3 shows the reduction as function of the error in the control law.

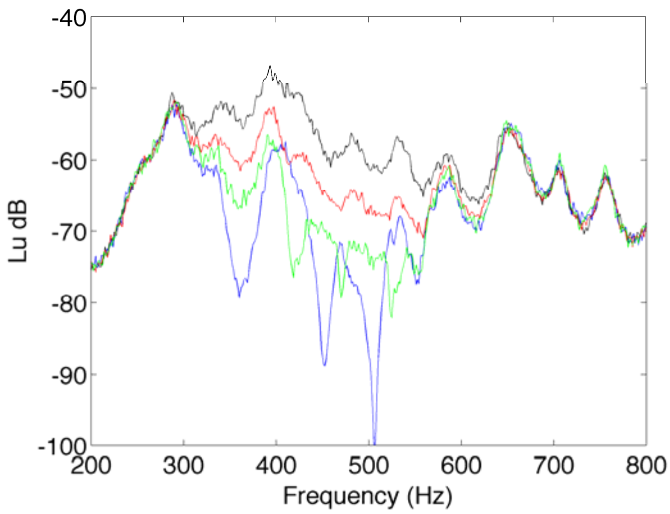


Figure 3: Sensitivity to an erroneously estimated reference signal. Blue: correct estimation, green: 25% relative error, red; 50% relative error, black: signal levels at the error microphone without control.

In WP4 a resonator was designed which is suitable to fit in the engine compartment of the Fiat 500 (see Figure 4). For the evaluation a recorded signal inside the opening of an intake system for an run-up supplied by FIAT CRF is used. The recorded signal is played through the primary source. For this an inverse filter of the primary path was designed in order to ensure similar levels over the frequency range in the experiment as measured at the engine. The results from the experimental evaluation are shown in Figure 5.

Figure 4: Photo of active Helmholtz resonator (in red) mounted to inlet pipe. The lower section of the AHR is the resonator, the upper section is the loudspeaker enclosure. © Centro Ricerche Fiat

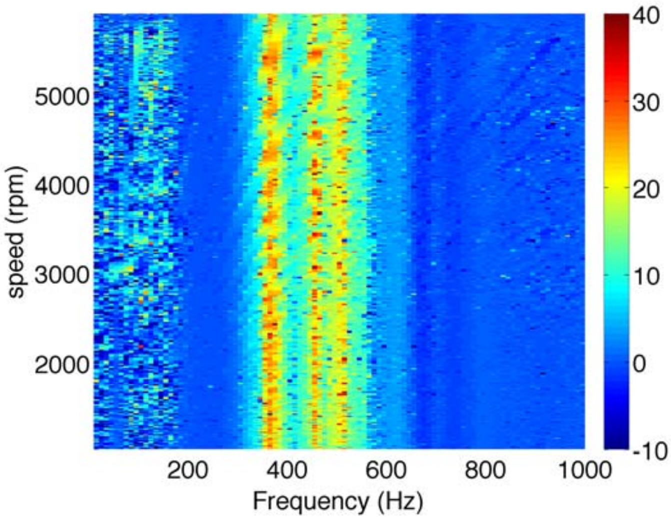


Figure 5: Achieved insertion loss for the active Helmholtz resonator under a simulated run-up. The control range was 350 to 550 Hz.

Finally the concept was implemented in the Fiat 500. Two conditions were tested: idle, and a slow run up from idle to ~5800 rpm. In Figures 6 and 7 the spectrogram for an idling engine can be seen. The error is bandpass filtered for 490–600 Hz, which then becomes the working range of the controller. The unwanted harmonics are reduced by ~15 dB. The measurement position is close to the error microphone, and the bonnet is open. Figures 8 and 9 show the resulting sound at the inlet pipe microphone for the engine run up (bonnet closed). A bandpass filter of 300–600 Hz is used. The strong unwanted harmonic disturbances are reduced by ~10–25 dB.

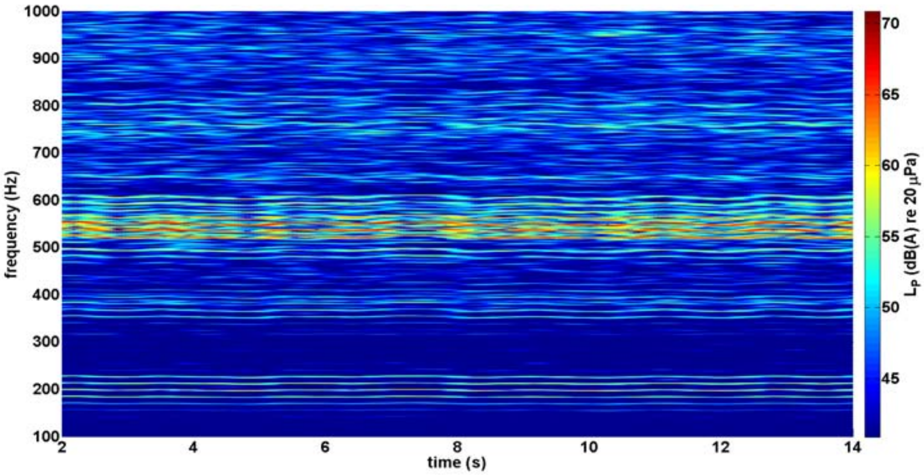


Figure 6: Spectrogram of intake noise, close to inlet. Idle engine. without control.

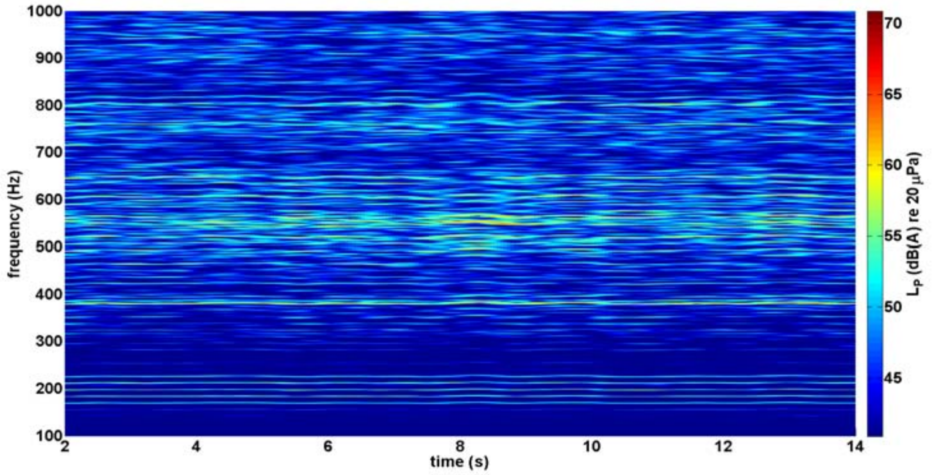


Figure 7: Spectrogram of intake noise, close to inlet. Idle engine. with control.

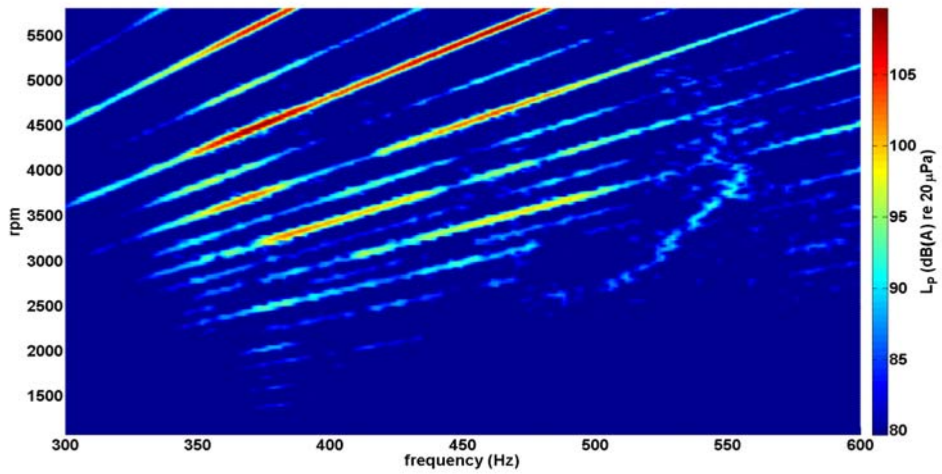


Figure 8: Spectrogram of intake noise, close to inlet. Runup 3rd gear. without control.

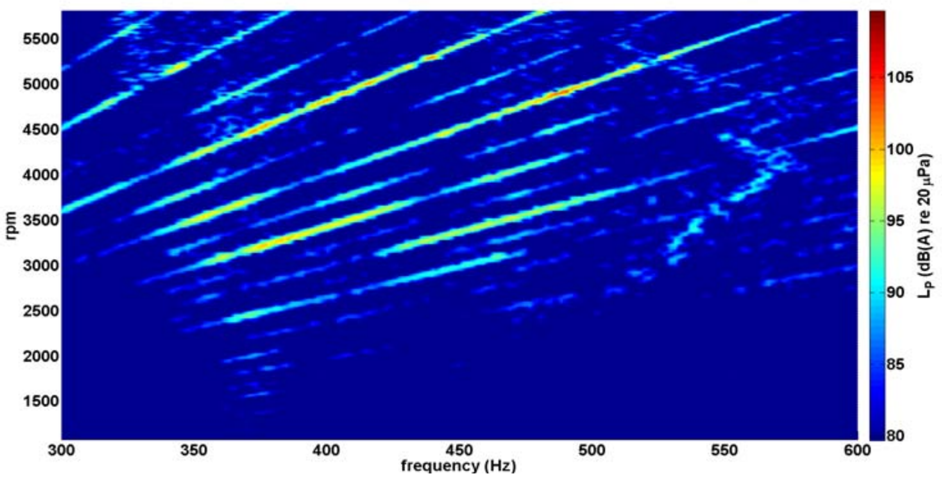


Figure 9: Spectrogram of intake noise, close to inlet. Run up 3rd gear. with control.

Although the reduction was substantial at the opening of the intake system, the reduction was only marginal for the exterior and interior noise due to the presence of other sources dominating the total sound.

For the intake noise, the controller is effective, by achieving ~10–25 dB for both run-up and about 10 dB for idle condition. It should be noted that the tested controller, could have been further optimised by introducing a normalisation filter, and further optimise the parameters involved in the controller. Furthermore the implementation of the harmonic controller could not be tested due to time constraints at C.R.F.

The reduction at other receiver position, however, was quite limited. Some reductions could perhaps be attributable to the controller. Due to the limited amount of testing, the small variations seen could also be random. In Figure 9 it can be seen that there is some reductions for the run-up case, although quite small, but another interesting aspect is that the major part of the energy is above 600 Hz, with a sudden strong band between 600 and 650 Hz. This suggests that the intake noise plays a limited part in the overall sound at this position (beside the left front wheel at 1.65 m height).

- The proposed controller together with the active Helmholtz resonator is effective in reducing the intake noise, as measured in the engine compartment.
- The reduction at exterior- and interior positions are quite limited, but some reductions are visible. Further testing and optimisation required.

Active Engine Mount

The given task for the active vibration and noise control system is to compensate vibrations excited by the engine of a small two-cylinder passenger car. It was decided to tackle the vibrations in x-direction of the car, which are mainly transmitted through the torque arm. This part connects the engine to the chassis and bears the torque of the engine; while the other mounts mainly bear the static mass (Figure 10).

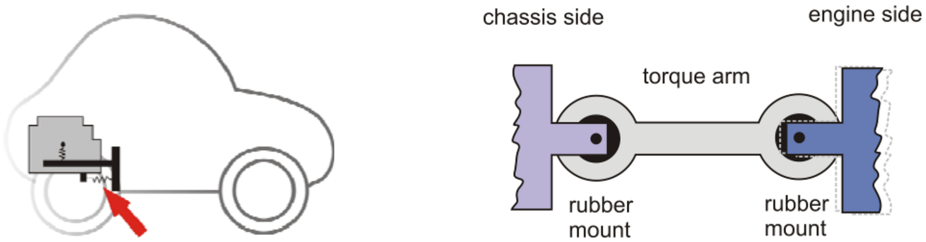


Figure 10: Position of the torque arm in the car (left) and basic design of the torque arm system

Control System

As described above, the task is the compensation of forced vibrations from the engine. A feed forward control concept is chosen, the block diagram is depicted in Figure 11.

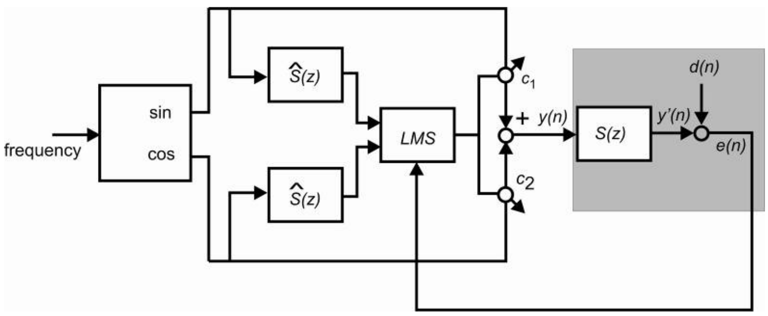


Figure 11: Feed forward control concept for the reduction of forced vibrations

Sensor and Performance function

Several sensors could serve as input for the control system. Widely applied are microphones inside the passenger compartment, force sensors integrated in the mount systems and accelerometers mounted collocated to the torque arm. Here, the sensor should be suitable for easily being retrofitted for tests. Thus, the accelerometer was decided to be the most suitable choice.

Actuator

For active engine mount systems, several general design concepts are known. Actuators might be integrated directly into the mount and carry also static loads or mounted in parallel to existing load carrying elements. Table 1 depicts the alternatives.

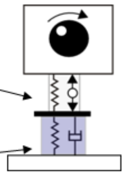
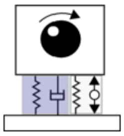
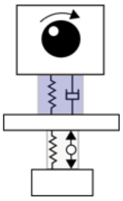
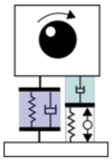
Actuator Elastomer Mount				
Type	Series Connection	Parallel Connection	Inertial Mass Actuator	Parallel-Series-Connection
Actuator Type	Stiff	Soft	Soft	Stiff
	■Examples: InMAR, AAL ■Modification of mount system	■ typically Electrodynamic actuator ■Modification of mount system	■Several actuator principles possible ■Additional space, additional mass ■ Flexible design	■Design of a damper with low (!) stiffness in series to a piezo

Table 1: Actuator principles considered

The inertial mass actuator was chosen, since it requires rather small modifications to the torque arm system and can be flexibly mounted into various test environments.

The basic principle of this actuator is depicted in Figure 12. Since the actuator utilizes inertial forces from a softly sprung mass, it is effectively driven only above its resonance frequency.

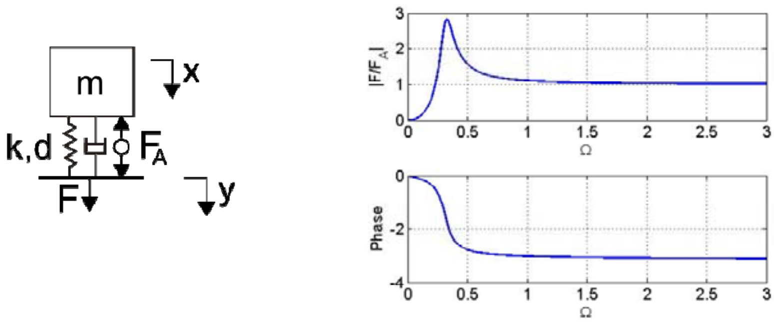


Figure 12: Principle of the inertial mass actuator, frequency response function of blocked force

When using electrodynamic actuators, the internal actuator and the stiffness element can be chosen nearly independently, since available electrodynamic actuators only possess a minimal mechanical stiffness. In contrast to that, piezoceramic actuators possess a quite high stiffness. This makes them suitable for contributing to the static stiffness of the system, i.e. to partially carry the inertial mass. However, the generated force and the stiffness are now connected by the equations of piezoelectric actuation, e.g. for a piezo multilayer actuator:

$$F_A = d_{33}kUn$$

Due to the high stiffness of the piezoelectric elements, the resonance of the system for a given mass would be much too high. Thus, the mechanical impedance of the piezo actuator has to be trans formed with suitable lever mechanisms (Figure 13). This configuration is also usually called *stroke-amplified* piezo actuator.

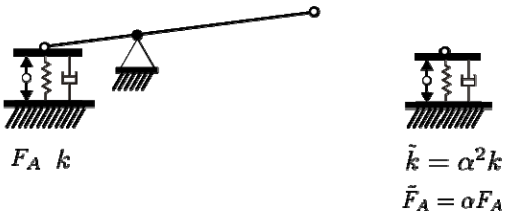


Figure 13: Stroke amplified piezo actuator

Three concepts, which all make use of some stroke amplification, were studied. Concept 1 includes a stroke amplified piezo multilayer actuator with a mass mounted on top of it. The second design is similar to the well-known piezoelectric beam. The third concept is based on structural integration of piezoelectric foils into to a cup spring of glass fibre reinforced plastics.

The first two concepts have to be used in a symmetrical configuration in order to just excite normal forces and compensate bending moments. This also doubles the available blocked force.

<u>Stroke Amplified Actuator</u>

A stroke amplification mechanism including solid state joints for the coupling of the piezoelectric actuator has been designed. Most stroke amplification systems are rather not rigid but have to be considered as a complex combination of lever mechanism and elastic elements. After promising results of a first prototype a second prototype has been designed (Figure 14). It works with four piezoelectric stack actuators distributed on both sides of a mounting. The advanced design leads to a balance of moments and a higher compactness of the actuator.

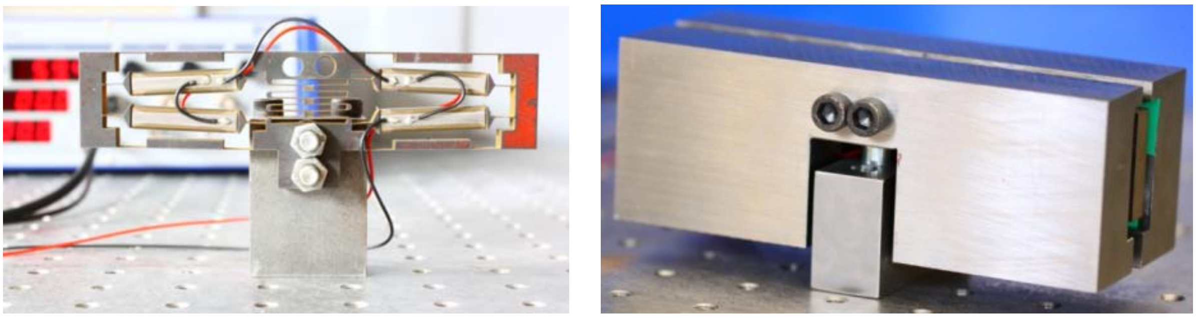


Figure 14: Inertial mass actuator based on a stroke amplified piezoelectric actuator – stroke amplification (left) and assembled system (right)

Two prototypes were set up:

- A stiff actuator with a resonance of 38 Hz
- A soft actuator with a resonance of 21 Hz

During block force measurements, some nonlinearity was observed: At higher driving voltages, the force of the stiffer actuator contained a significant amplitude at the 5th harmonic which also deteriorated the frequency response measurement (Figure 12 and Figure 13).

<u>Bending Beam</u>

This concept consists of a piezoelectric patch actuator glued to the surface of a clamped beam with a tip mass. Several prototypes have been set up for investigation. A CFRP beam was used for a stiffer actuator, while a GFRP beam lead to a lower resonance of about 22 Hz (Figure 15). However, the bending beam actuators both possess a 2nd resonance in the frequency range of the relevant engine orders of a 2 cylinder city car (Figure 16).

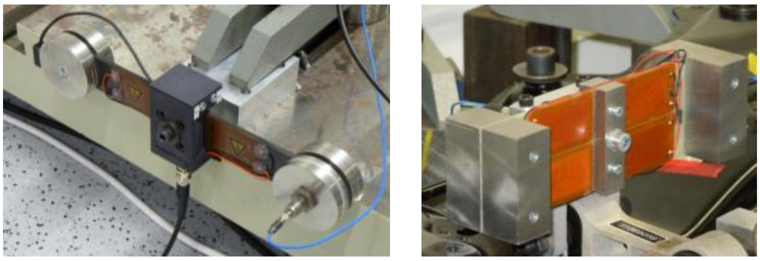


Figure 15: Inertial mass actuators with bending beam and tip mass, stiff actuator (left) and soft actuator (right)

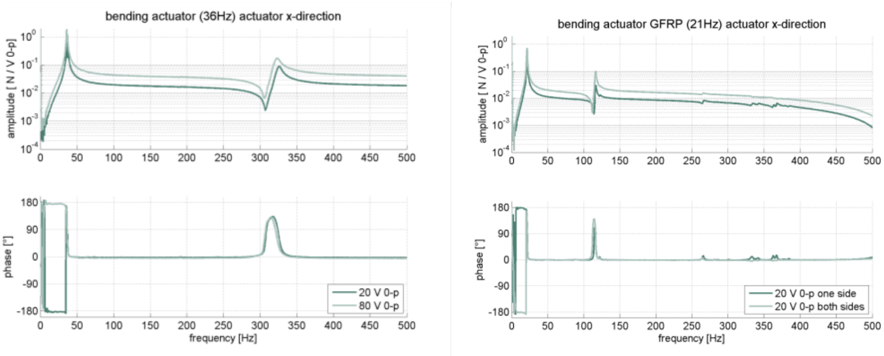


Figure 16: Block force measurements, stiff actuator (left) and soft actuator (right)

<u>Cup Spring with integrated piezoelectric elements</u>

The design of a disk spring with integrated piezoelectric foils could lead to a quite compact actuator system. In the first step, the feasibility of the physical integration of piezoelectric foil modules into GFRP is evaluated. A simple prototype has been set up and characterised before optimization of the shape towards a curved disk (Figure 17).

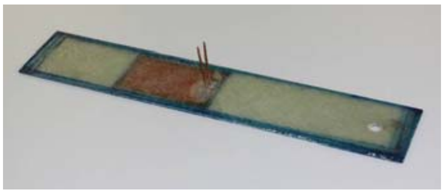


Figure 17: GFRP coupon with integrated piezo foil module

Finally, a prototype of a cup spring actuator made of glass fibre reinforced polymer (GFRP) with integrated piezoelectric foils has been designed and implemented. The stiffness of the cup spring must be regarded as a parallel connection of piezoelectric foils and GFRP-structure.

The design uses two cup spring actuators connected in series, each with five integrated actuators (Figure 18).

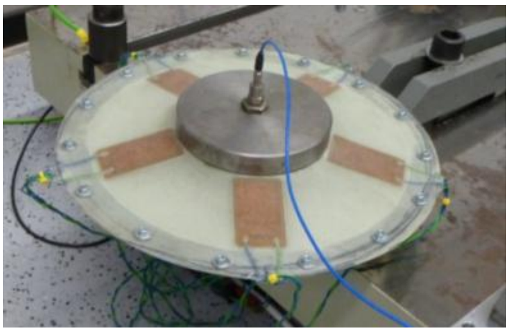


Figure 18: Final design with two cup springs connected in series and five integrated actuators

Evaluation of the final designs

Dynamic measurement in x- (operational) and z- (upright) direction were conducted in order to investigate the sensitivity of the parameters to gravitational influences. The most relevant parameter is the block force, which was derived from a measurement of the acceleration of the mass by Newton's law. A frequency range from 0 Hz to 500 Hz and two amplitude ranges (0V – 40V and 0V-160V) were used in order to test the linearity of the actuator. A sine excitation at 100Hz was used to check whether higher harmonics in the actuator force are present. Table 2 summarizes the results of the investigation.

IMA	2nd resonance [Hz]	Max driving voltage [V]	Mass [kg]	Blocking force [N] 100 Hz 20V 0-p Z (X) direction	Blocking force [N] 100 Hz 80V 0-p Z (X) direction
Bending beam 21,3 Hz	200	-100 to +400	2	0,4 (0,4)	0,8 (0,8)
Bending beam 37,5 Hz	320	-100 to +400	1,5	0,7 (0,8)	1,6 (1,7)
Stroke amplified 21,5 Hz	420	0 to +200	1,9	2,6 (2,5)	6 (5,7)
Stroke amplified 36,3 Hz	380	0 to +200	1,9	3,8 (3,7)	9,0 (9,1)
Cup spring actuator 52,5 Hz	75	-100 to +400	2		

Table 2: Results of the measurements at the inertial mass actuators

Electro-magnetic actuation for Cabin Active Noise Control

The overall aim of this part of the project is to reduce the sound radiation into the vehicle using actively controlled electro-magnetic actuators on the panels. The concept is of a self-contained multi-functional control unit, using an inertial mass actuator, inbuilt sensor and local feedback controller, to reduce the vibration of individual panels on the vehicle, as illustrated below. One advantage of such a control module is that it is self-contained and can be mass produced using established, inexpensive technology for the actuator and sensor. A low natural frequency for the actuator is required for good stability of the feedback loop, but this compromises the robustness of the unit because the spring is then so weak. An analogue compensator design has been developed to overcome this problem, which has been tested on a number of small commercial inertial actuators with a natural frequency of 50 Hz and it has been shown that the compensator is effective in reducing the resonant frequency to 10 Hz even in the face of normal manufacturing tolerances.

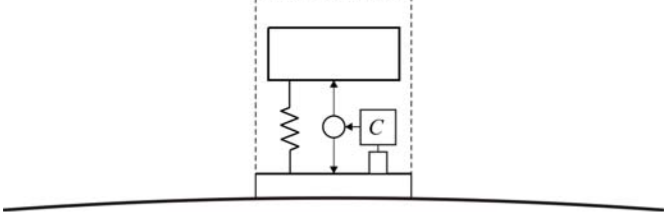


Figure 19: Active-control module using an internal actuator and local feedback loop driven by inbuilt sensor.

Inertial actuators can significantly influence the dynamics of a structure due to their passive loading effect, as well as a result of active feedback control. The passive effect is normally closely linked with the influence of the feedback controller, however, and independent design of the actuator for these two purposes is not generally attempted. A compensator can be used in the feedback controller to separate the range of frequencies that are actively controlled from the frequencies at which the passive loading due to the actuators dynamics has most effect.

A practical example of such a compensator is used to actively control the vibrations both on a panel and on a beam, as shown in Figure 20. The influence of the actuator as a passive tuned mass damper can be clearly seen in Figure 21 before the feedback loop is closed, and broadband damping is then additionally achieved by closing the feedback loop. The compensation has been found to greatly increase the feedback gain that can be used and also to separate out the design of the active control system from the design of the actuator as a passive tuned mass damper. An electromagnetic actuator can thus be designed to be truly multifunctional.

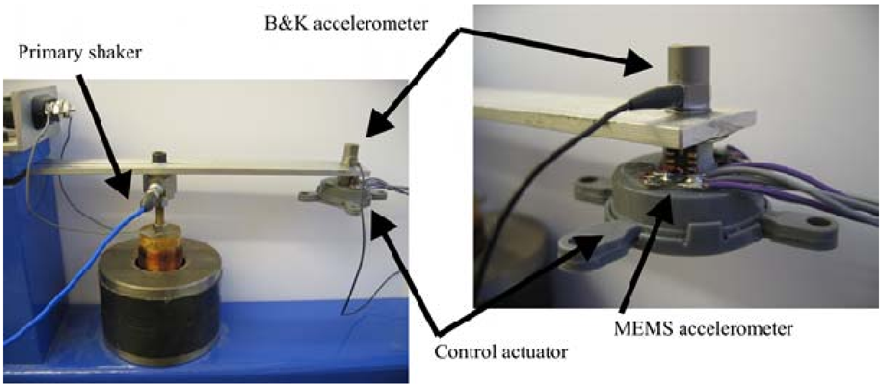


Figure 20: Experimental set-up for measurements on a cantilever beam.

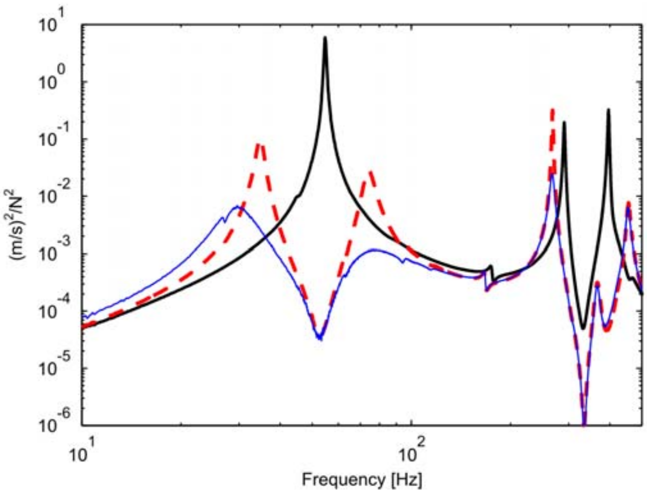


Figure 21: Measured control point velocity response on the beam per unit excitation force, without control unit (solid-black), with open-loop control unit (thick-dashed), beam with closed loop control unit (thin-line).

For the car application CRF suggested the roof panel as a potential final application for the self-contained active control units. For this application a small inertial actuator has been developed as shown in Figure 22. The transducer unit used as a proof-mass electrodynamic actuator was a 60-mm diameter cone loudspeaker manufactured by Pro Signal, type S066M. These actuators are mass-produced and commercially available at a very low cost. They are lightweight and their high stiffness makes them relatively robust. Therefore, they are suitable for the implementation of a light weight and cost effective velocity feedback control system. In order to achieve effective coupling between the loudspeaker moving mass and the vibrating surface, the cone of the loudspeaker was filled with silicone acetate sealant. A thin plastic disk was then fixed on the filling to ensure a level and smooth contact surface. The silicone acetate was chosen after trying different possible fillings because of its light weight, ease of application and flexibility. These properties allow the loudspeaker diaphragm to move freely and react against the surface when being driven.

Figure 22: Actuator unit, a 60-mm diameter cone loudspeaker (Pro Signal, type S066M)

To understand the limitations on controlling the roof panel simulations have been performed of feedback control using this inertial actuator on curved panels and the effect of curvature on the mode spacing has been found to significantly influence the predicted performance. A roof panel has been supplied by CRF which has been tested and the performance of an ideal point force velocity feedback control system consisting of four units has been predicted and the results are shown in Figure 23. From this plot it can be seen that due to the modal clustering caused by the curvature of the roof panel, control is only achievable at very low frequencies.

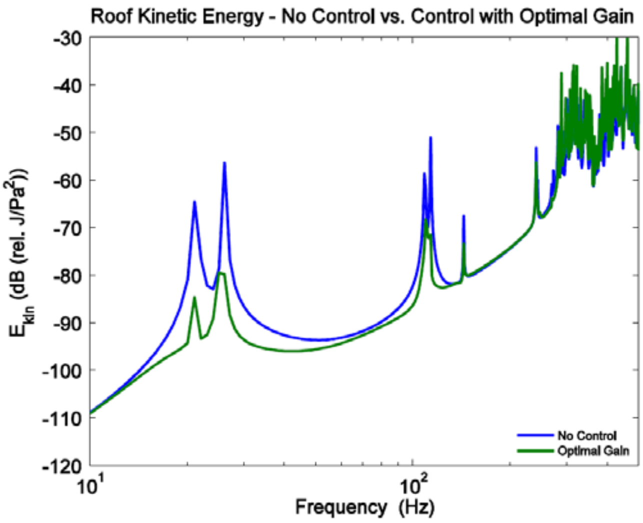


Figure 23: Simulated performance of multichannel feedback control system with 4 ideal point force controllers on the roof panel.

In order to assess the performance of the self-contained control unit including the designed compensator a series of measurements have been conducted on the enclosure presented in Figure 24. This experimental setup allowed the curvature of the aluminium panel to be varied by pressuring the air-tight Perspex box.

Figure 24: Experimental setup for testing the performance of the self-contained control units on a panel

Figure 25 shows the kinetic energy and optimal gain graphs for the flat and doubly-curved panels without control and with the uncompensated controller and the compensated controller. For the uncompensated system there is limited distance between the optimal and maximum stable gain points and most of the attenuation in the structural response is due to the passive effect of the actuator rather than the feedback controller. However, when the compensator is added to the feedback loop, the maximum stable gain and the gain margin are both significantly increased. For the flat panel, attenuation in the kinetic energy level of the first few modes is significant and the first peak shows an attenuation of 20 dB. For the curved panel the overall attenuation is only around 2 dB, however, the designed compensator produces a controller with an optimal feedback gain well below the maximum stable gain.

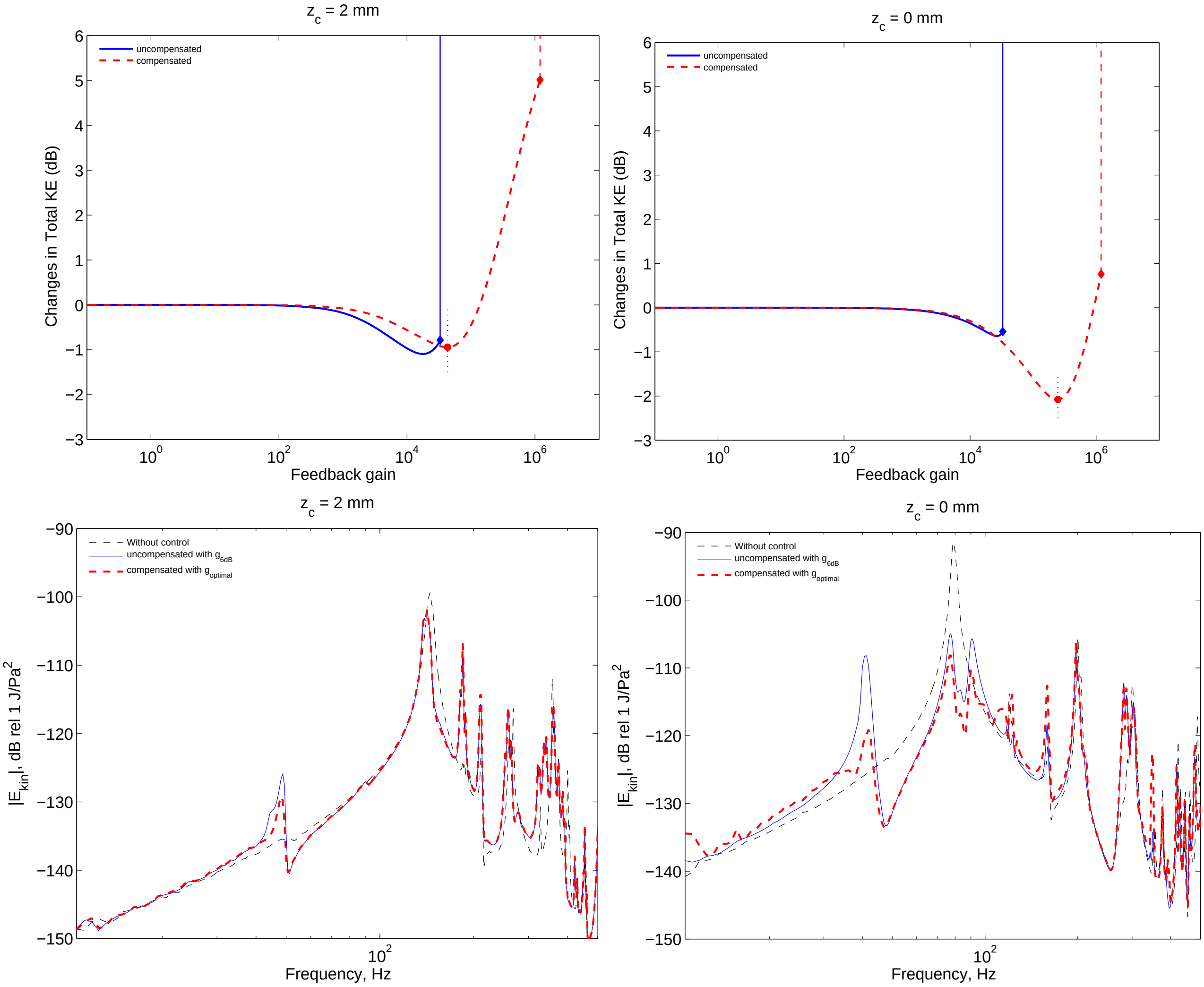


Figure 25: Kinetic energy (left) and optimal gain plots (right) for flat and curved panels: maximum stable gain (diamond) and optimal gain (circle)

Integrated feed-forward and feedback active noise control system using loudspeakers

Active noise control systems offer a potential method of reducing the weight of passive acoustic treatment and, therefore, increasing vehicles' fuel efficiency. These can be particularly cost-efficient if integrated with the entertainment system. A combined system has been investigated that employs feedforward control of engine noise and feedback control of road noise, using a 'modal' error signal, as below.

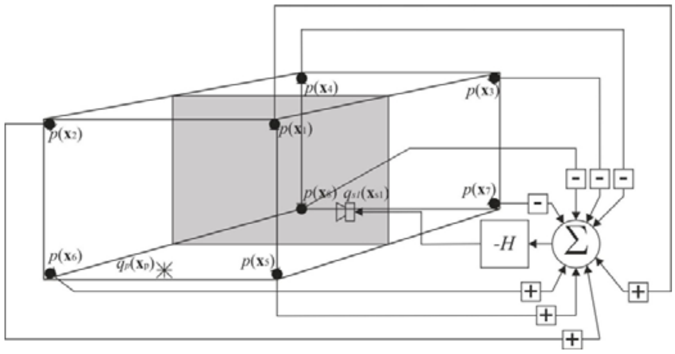


Figure 25: Modal feedback control system.

Due to the dependence of the feedback system on the modal response of the vehicle cabin, and the influence of structural-acoustic coupling on this response, the effects of structural-acoustic coupling upon the performance of the active noise control strategies has been investigated. An elemental model of structural-acoustic coupling has been derived and used to simulate the change in performance of the active control systems as a result of coupling; the feed-forward component is largely unaffected by structural acoustic coupling, whilst the modal feedback performance is reduced from 11 to 8 dB attenuation in total acoustic potential energy, due to the shift in the frequency of the targeted acoustic mode. The simulation results are confirmed through experiments conducted in a structural-acoustic coupled enclosure, the results of which are shown below.

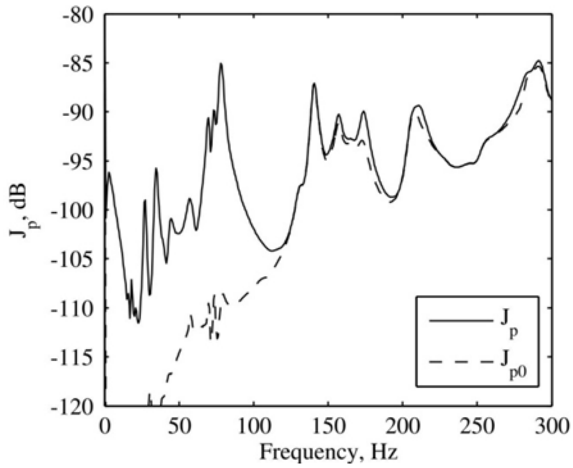


Figure 26: Estimate of total acoustic potential energy before and after simulated global feedforward control using experimentally measured responses for a single secondary source.

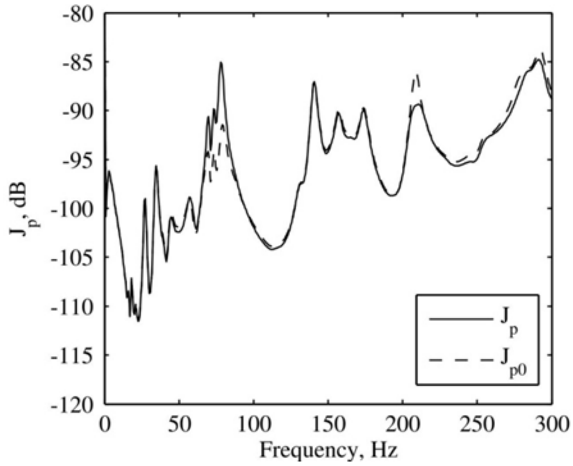


Figure 27: Estimate of total acoustic potential energy before and after simulated modal feedback control using experimentally measured responses with a single secondary source and a maximum error signal enhancement of 6 dB.

To determine the potential performance of the proposed active control strategies a series of measurements have been conducted at CRF on the 2-cylinder 875cc Fiat 500. These measurements consisted of the characterisation of the acoustic environment in the car cabin, including both transfer response measurements between the four car audio loudspeakers and a set 16 microphones and measurements of both engine and road noise.

The engine noise measurements highlight that the dominant order is the first engine order and offline simulations have been conducted to predict the level of control that may be achievable using a feedforward control strategy. These predictions are shown in the Figure below. A real-time engine noise controller has been developed and has been tested at CRF by ISVR to validate the predicted levels of control.

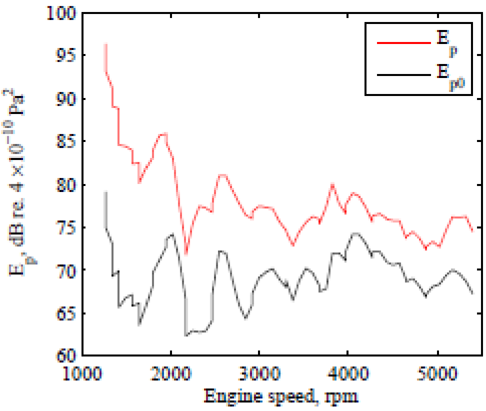


Figure 28: The acoustic potential energy estimated from the 16 pressure measurements due to the first engine order before control (black line) and after optimal feedforward control (red line).

The road noise measurements have shown that there are two components that may benefit from active noise control. From the results presented in Figure 29 it can be seen that there is a broadband peak between around 80 and 180 Hz and two narrowband peaks at around 240 and 260 Hz. Using the modal control strategy it has been predicted using offline simulations that although reductions of up to 10 dB in the modal error signal are possible, as shown by Figure 30a, the acoustic potential energy shown in Figure 30b is hardly altered. This is believed to be due to the fact that the enclosure's response over the targeted bandwidth has contributions from a number of acoustic and structural resonances, which are excited in a complex way by a number of uncorrelated noise sources, and the single channel controller cannot independently control each of these resonances. To improve this control a multi-input- multi-output control strategy is currently being investigated.

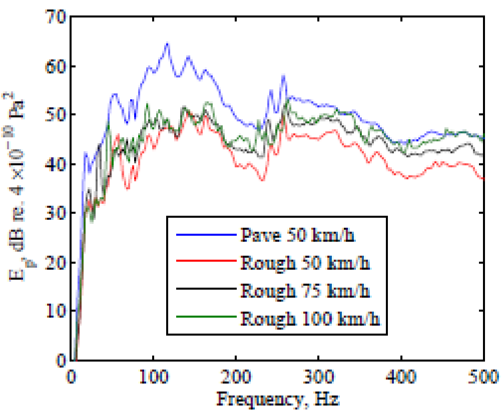
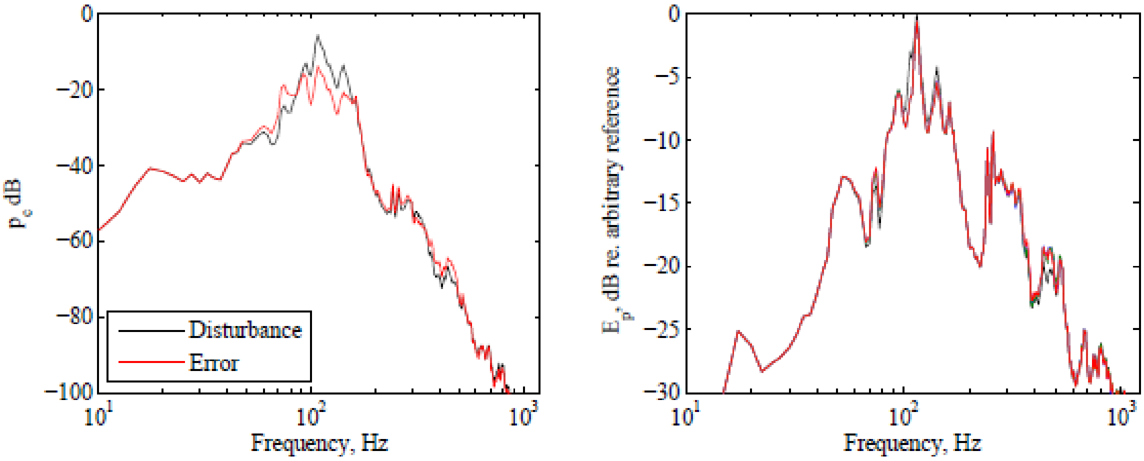


Figure 29: The A-weighted acoustic potential energy estimated from the 16 microphone measurements for constant road speeds on the pave and rough road surfaces.



(a) The A-weighted composite disturbance and error signals (b) The A-weighted acoustic potential energy estimate before and after control.

Figure 30: The predicted performance of the feedback controller employing eight spatially weighted microphones and four spatially weighted car audio loudspeakers and a temporal filter. The level in each case is shown before control (black lines) and after control (red lines).

Application and Validation of Cabin Active Noise Control

In WP2 it was predicted using offline simulations that the developed engine noise control system may offer significant levels of noise reduction at the first engine order. A real-time controller has been implemented in the Fiat 500 to validate these predictions using a DSpace controller, three control loudspeakers and four error microphones, as shown in Figure 31. The microphones were positioned at the headrests as shown in Figure 32.

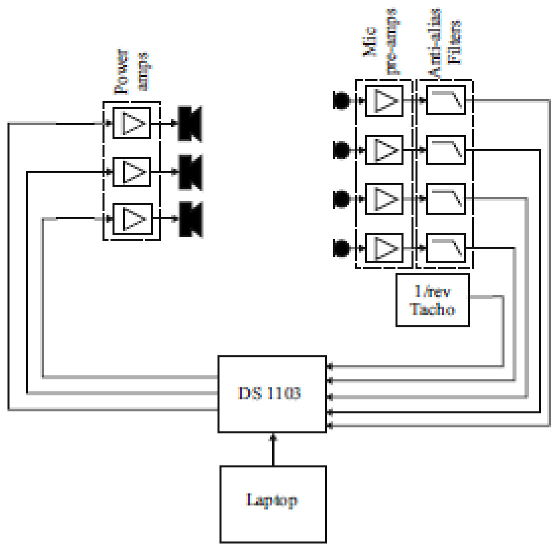


Figure 31: Feedforward controller setup consisting of four error microphones, and 3 control loudspeakers. The once-per-rev signal is obtained directly from the engine.

(a) The mounting and positioning of the two front microphones will be the same as the outer two microphones in this photo.

(b) The mounting and positioning of the two rear microphones will be the same as the outer two microphones in this photo.

Figure 32: Microphone positioning and mounting.

The performance of the feedforward active engine noise controller was measured under a number of operating conditions and, for example, Figure 33, shows the sum of the squared error sensors at the frequency of the first engine order for a fast run-up in 3rd gear with two different convergence coefficient settings. The level of noise reduction was objectively significant, however, not subjectively so and future work could improve the subjective impression of the attenuation by developing the controller to control multiple engine orders.

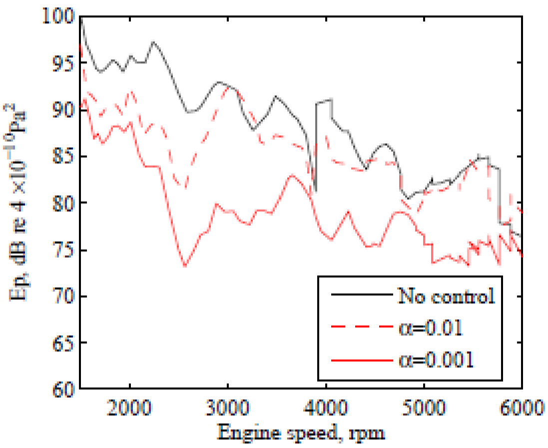


Figure 33: The sum of the squared error sensor pressures at the first engine order plotted indecibels relative to 4×10^{-10} Pa^2 for a fast engine run-up in 3rd gear with active control system off (black line) and on (red lines) with different convergence coefficients.

New Materials and Components for Sound Packages

In the framework of the project WP3, several different development activities were initiated and successfully completed in the field of vehicle sound package acoustic treatments. The main final objective is the achievement of 20% weight reduction with respect to the current demo vehicle sound package (Fiat 500 twin-air) without deteriorating the vehicle acoustic performance.

A new type of constrained layer damping treatment based on a thin aluminium foil applied on a new special type of bituminous layer was developed and prototyped. The new type of bitumen has remarkable elongation and resilience properties, sufficiently high stiffness to insure proper panel constraining, good formability at room temperature, and low weight per unit area. The weight of the new lightweight constrained damping treatment lies between 20% and 50% below the average state-of-the art damping treatment, while the vibro-acoustic performance is at least the same as a standard single layer damping treatment.

Also new technologies combining low weight with good acoustic and thermal properties (i.e. acoustic absorption and/or insulation performance) for engine bay applications were successfully developed and investigated. The first technology is a glass-free lightweight foam having good formability and thermal stability properties combined with high acoustic absorption. This material is suitable for non-structural thermo-acoustic engine bay applications like hood liner or dash outer components. The new thermo-acoustic lightweight foam outscores the acoustic absorption performance of melamine foam, and compares very well to that of glass wool with the same thickness and up to 80% less weight.

A second novel technology for engine bay applications successfully developed is a new fiber-based material for high temperature applications providing a remarkably good combination of stiffness and acoustic properties, together with high durability, thermal stability, and flammability properties. The material is suitable for structural thermo-acoustic engine bay components thanks to its self-carrying properties (stiffness), thus it can be used either as a stand-alone layer for thermo-acoustic insulators, like for instance engine-mounted covers, or as a carrier for other absorbers for enhanced acoustic performance. A particularly effective combination in this sense is a double layer made of the fiber-based material as a lightweight and stiff thermo-acoustic carrier and the thermo-acoustic lightweight foam as an acoustic absorber. The acoustic absorption of such a double layer is remarkably high (above 70% from 630Hz).

For applications in the interior passenger compartment, a novel hybrid concept particularly suited for inner dash insulator applications (but also extendable to floor carpets and other interior parts) was developed starting from flat layers of raw materials. After an initial material characterization phase, the most promising layer combination in terms weight and acoustic performance was selected on the basis of experimental and simulation analysis at part and vehicle level. A part based on such a hybrid concept combines the typical advantages of conventional mass-spring multi-layers component (acoustic insulation) at low-mid frequencies combined with those of an absorption type multi-layer component (acoustic absorption) at mid-high frequencies. Prototype layers made out of the novel hybrid concept were manufactured and made available for sound package component prototyping.

A new heat shield special embossment configuration having same durability as standard heat shields with up to 20% weight saving was developed. The new embossment pattern could be implemented after extensive experimental and numerical analysis, with particular reference to heat shield fatigue behaviour. Last but not least, a new fiber-based concept for underbody application saving up to 50% with respect to the standard state of the art was developed and layers made available for underbody shield prototyping.

Besides the different acoustic treatment concepts and materials, a numerical and experimental optimisation activity of the treatment and grommets of the front end of a Volkswagen D-segment car was carried out in order to better understand the influence of the grommet areas and find out the best compromise between weight reduction and inner dash wall treatment performance. The results of this work show that optimising the grommet configuration is very effective in improving the global acoustic insulation performance of the front end, and a corresponding relevant amount of weight can be taken out from the upper dash treatment heavy layer.

The last WP3 phase involves the manufacturing of prototype sound package components for the demo car using the new technologies mentioned above. Prototype components are mainly manufactured by hand (except the engine side cover and the engine top cover, whose prototypes have been made using prototype tools).

The new glass-free thermo-acoustic lightweight foam is used for the demo car hood liner and outer dash prototype components, saving respectively 35% and 62% weight with respect to the standard original components mounted in the demo car. The new fiber-based material for high temperature applications combined with the previously mentioned lightweight foam is the selected technology for engine top and distribution chain cover prototypes. These two parts are both manufactured using prototype tools and help to save respectively 4% and 75% against the original demo car components.

The novel hybrid concept for interior is used to manufacture the inner dash wall treatment prototype component. The part is extended towards the cowl sides and tunnel areas, and the grommet acoustic performance has been improved according to the findings of the VW front end activity seen before, bringing larger coverage and improved acoustic performance with 38% weight saving with respect to the standard original demo car dash wall treatment. A single aluminium layer with the special embossment configuration is used to prototype the tunnel outer shield. This is combined with a lightweight foam absorber in order to enhance the component acoustic performance keeping the same original component weight. The new fiber-based technology is used to prototype the under engine shield (53% weight saving against the original component) and the engine side shield (42% weight saving against the original component). New formable constrained layer damping treatment patches were manufactured by hand fitting the areas of the demo car original damping package with a weight saving of 21%.

The demo car prototype sound package brings a weight saving of approximately 20% with highly improved component acoustic performance thanks to the new technology concepts.

Innovative Tyres

Due to legislative changes within the EU there is an increased demand for improvements in car tyre rolling resistance and noise generation. Apart from measurement data, however, information about the relationship between rolling resistance and rolling noise generation is scarce. It is the goal of this study to investigate the fundamental physical processes connecting both areas. Additionally, it is evaluated whether a simultaneous reduction of both rolling resistance and rolling noise is possible or if this is contradicting requirement. A previously presented model for simulating the structural dynamics and rolling resistance of a rolling car tyre is extended to allow rolling noise calculation. The approach is based on a waveguide finite element model of the tyre. Tyre/road contact forces are obtained using a non-linear 3D contact model. The velocity field on the tyre surface is used to determine the radiated sound pressure based on a boundary element method. In a parameter study it is evaluated how much dissipation and sound radiation are affected by material properties, tyre construction and road surfaces. Due to the characteristics of the modelling approach, detailed information about dissipation and sound generation in different frequency regions, wave orders or parts of the tyre is available. The results show that rolling resistance and radiation are mainly low wave order, low frequency phenomena which are, at least partly, controlled by the same set of modes. This suggests that by modifying specific tyre properties reductions in both sound radiation and rolling resistance can be achieved.

Besides the simulation approach innovative tyres with respect to low rolling resistance and low noise are built and tested. At the beginning of the development work a 175/65 R14 79 T Conti Premium Contact 2 was selected as a reference tire. This tyre size was selected in agreement with C.R.F. As the adaptation of WFEM existing model was done in the first year, it was not possible to convert the results of the parameter study into the first tyre constructions. Therefore the first loops of tyres were build and tested due to the know how in Continental. To achieve handling and rolling resistance targets (EU label A) a new mold was ordered and then the tyres were built. In the very first step the performance of the reference tyre was investigated. An innovation workshop was carried out to find ideas for the adaption of tread pattern, tyre construction and tread compound. In the following development loops the ideas from the innovation workshop were implemented and tests were carried out. In each loop up to 4 ideas were tested. In detail the following groups were build:

3 groups in loop1
3 groups in loop2
3 groups in loop3
4 groups in loop4
2 groups in loop5
3 groups in loop6
5 groups in final loop

In total 23 tyre variants were developed with different characteristics. From each of these developments up to 25 experimental test order tyres (ETO) were built for evaluation. Unfortunately neither the results of the first loops for rolling resistance (Cr ≤ 6.5 kg/t) nor the results for noise reached the targets. At the end seven loops of tyres were built to reach an acceptable level.

Besides the optimization of the tyres in development loops further investigations were done to find out what can be done to optimize the tyre NVH features:

- To study the radiation behaviour blank tyres were built and in a carving study the influence of longitudinal void on the radiated noise was studied. It was found out that tyres with an even number of longitudinal grooves are less noisy than tyres with an uneven number of longitudinal grooves.
- To optimize the noise inside the vehicle tyres with Conti Seal were built. By adding absorbing material inside the tyre the vibrations of the air column inside the tyre (cavity mode) could be lowered significantly.
- An important transfer path of the structure borne tyre noise from the tyre/road contact to the rim is via the tyre sidewall. A stiff sidewall leads to a good transmission of the vibrations but is good for low rolling resistance as the deformation of the tyre is smaller. An increase of innerliner material offers the highest potential to alter the NCB performance. A special bead technology is not affecting too much the tire performance. An increase of the amount of material in the sidewall shows potential to reduce the NCB performance but is altering the rolling resistance performance even more.
- Another set of tyres were build to evaluate the behaviour of tyre belts. The triangle belt is 1.3 dB louder than standard belt at 80 km/h. Also the half belts show nearly the same level increase. But a variation of the belt construction itself shows potential to alter the NVH performance.
- The influence of thicker under tread was evaluated with another set of tyres and a potential of up to 1,8 dB was found.
- In another study different tread compound were compared. As a reference a normal passenger car tyre tread compound was chosen and compared with three tread compound normally used for truck tyres. It was found out that truck tread compounds show a potential to improve both at the same time rolling sound and rolling resistance. But truck tread compounds are showing a clear target conflict between rolling resistance and wet braking while the rolling sound performance is not significantly altered. A spread in ShA of 10 gives a sound level difference of 1,8 dB(A) which gives a potential of 1 dB(A) for the measurement accord. R117.
- The vibration behaviour of a standing tyre is understood but it is not completely understood what happens if the tyre is rolling. With accelerometers on the innerliner the vibrations of a rolling tyre were studied. It could be shown that the modal behaviour is lost in a rolling tyre.

Putting all results together no solution was found with an EU label A in rolling resistance and only 1sound wave as noise label in one tyre construction. The best tyre for rolling resistance was built in loop3 (Cr ≤ 6.5 kg/t = EU label A). In the final loop the best tyre for exterior noise was build (EU label 1 sound wave and 67 dB). Tyre 4 of the final loop was chosen as the best compromise in NVH between exterior and interior noise. This tyre was sealed for better cavity performance and send to CRF for final use in GCC.

Identification of noise sources intensity

The interior of the car cabin was assessed in terms noise sources intensity in the cabin and their contribution to the driver's position using Conformal Noise Source Identification and Panel contribution techniques developed in EU Credo project. From the calculation of intensity in terms of Sound Power from the panels it is seen that most energy is generally radiated from floor. However, by introducing the panel contribution it turns out that at low frequencies it is actually the windshield that contributes mostly at driver's head position. This is confirmed by displaying the pressure FRF's where high levels are seen especially at the corners of the windshield at low frequencies. Another important contributor is the rear part of the floor, which introduce high pressure at the 800 Hz third octave band. Finally, another interesting observation to mention is that the dashboard contributed very little compared, although it is the largest of the considered panels, and it is very close to the driver. This indicates that the sound is effectively prevented from entering the cabin through the firewall/dashboard.

Wireless Sensor System

Reduction of noise from new lightweight engines will require that the transmissions path is handled as close as possible to the primary sources. For combustion noise and piston slap, two major sources, vibrations shall possibly be tackled on the crank mechanism before they reach the main engine structure. This requires sensors to be placed at the piston and on the conrod with top level characteristics and the ability to transmit data out the engine to make analysis and comparisons with simulations.

The environment inside the engine is however very harsh and requires special attention for design and implementation of the on the wireless sensor system with respect to temperature, shock and vibration levels and how the systems is powered while measuring. Within *Green City Car* a prototype of such a wireless sensor system has been developed. This will be able to work in these environments and which accommodates inductive energy transfer to supply sufficient energy for the transmission and conversion of data from inside the engine. Powering of the system via battery operation seems not feasible as the engine has to be dismantled every time the battery needs to be replaced and this takes very long time.

The overall design of the system can be seen in Figure 34 and the various modules in prototype implementation are shown in Figure 35.

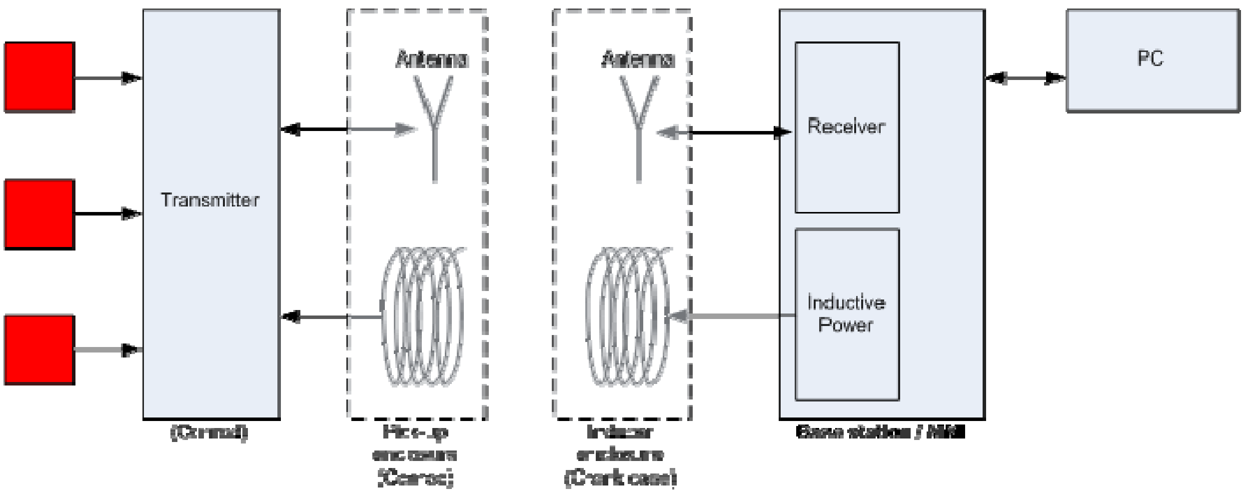


Figure 34: Overall design of the wireless sensor system (the red part is the transducers placed on the conrod)

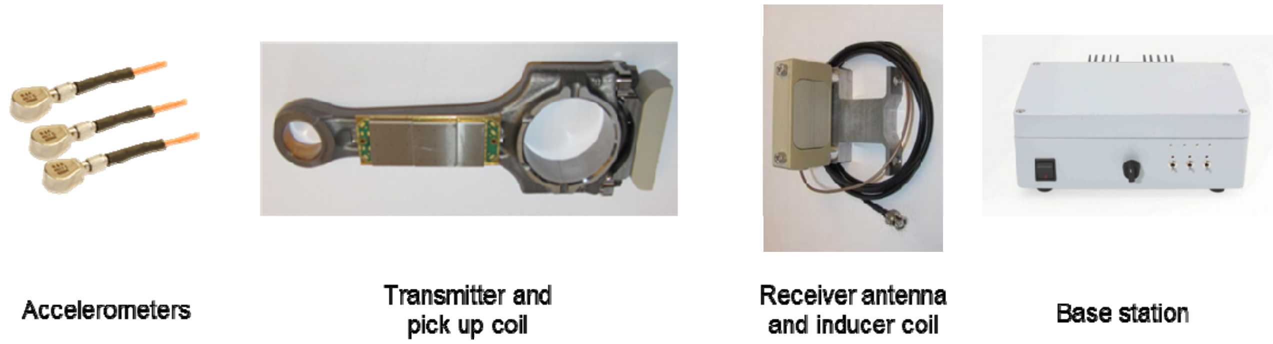


Figure 35: The various modules in the Wireless Sensor System

To pick up the vibration signals from the conrod and piston, 3 charge accelerometers are mounted at the specified positions for measurements of vibration levels at piston or on the conrod. The vibration signals are conditioned and digitized in the transmitter module. From here the data are transmitted to the receiver module through a 2.4 GHz Bluetooth antenna. The signals are sent to the PC via the Base station's receiver board. The vibration data are then recorded in a file while being monitored on a PC (see Figure 36). Later the recorded data can be further post processed and analysed in PC programs such as in th BKSV PULSE LabShop or PULSE Reflex.

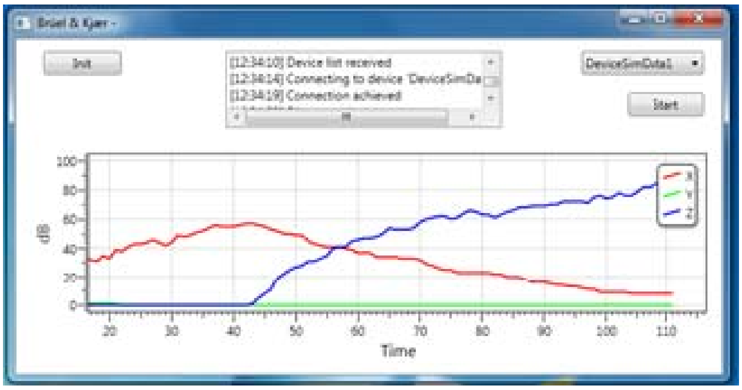


Figure 36: PC Software GUI example.

The base station transfers energy to the inducer coil module and the receiver module transfers the energy via an inductive coil system to power the transmitter on the conrod. To ensure a good Bluetooth connection and a stable energy transfer the receiver antenna and inducer coil is installed in the engines oil sump are just beneath the conrod. Currently, the system can transmit data over a stable Bluetooth link and sufficient energy can be transferred over the inductive coil system to make the transmitter work. To accommodate the necessary power for transmitter operation an energy reservoir is included to power the transmitter when the distance from pick up coil to inducer coil is too far away for each other to transfer energy.

Extensive temperature, shock and vibration tests of the various components and modules which are going to placed inside the engine and all components seems able to work at the specific temperatures and shock and vibration levels inside the engine. The data transfer still requires some optimisation to reach the required data transfer for good measurements. This includes amongst others optimisation of embedded transmitter and receiver software especially on the modulation scheme and the mode of operation in the μ-processor system.

Due to many problems with the BT software and poor software for the selected μ-processors this was not possible to be completed in the project time frame. As a result of this, real measurements and validation including comparisons with simulated data was not possible.

Validation & Demonstration

The base-line City-Car has been measured on Fiat test tracks representing the main road conditions (cobblestone, rough road, smooth road, engine run-up) and in semi-anechoic rooms at CRF in terms of Noise, Frequency Response Functions from vehicle suspensions for structure-borne path, Frequency Response Functions from engine-bay for air-borne path. Such collected data are to be used for the subsequent comparison with the same car provided with the new technology developed within the project. The adapted city car has been measured using the same procedures followed for the base-line. Mainly the global effect due to the new tyres and the new lightweight acoustic package has been assessed, whereas the contribution of each single technology has been described in the previous chapters.

A reduction in engine noise of up to 7 dB(A) has been detected at front passengers' ears during an engine run-up in third gear. A similar reduction in Sound Pressure Level is obtained for the rolling noise on pavè and rough roads, whereas about 2 dB(A) has been achieved on smooth road, for which the asphalt input is lower. A noticeable improvement in sound quality has also been achieved, with an increase in Articulation Index of about 5 counts.

4. The potential impact and the main dissemination activities and exploitation of results

Potential Impact

A modern society depends on safe, efficient, and environmentally-friendly technologies. However, it is an on-going challenge for the European industry to meet customer and legislative requirements and also satisfy societal demands within the competitiveness of the global arena under the aspect of a sustainable technology. In growing industrialised regions of the world a special focus has to be placed on less resource-intensive and knowledge-based, enabling technologies. The need for new technologies to meet not only customer demands but nowadays more important global needs such as reduction of CO_2 emission has always been a driving factor for economic growth. With the Kyoto Protocol combating the global climate change through reducing or reversing the greenhouse gas (GHG) emissions in the industrialized nations, the global automotive industry is facing new challenges. New constraints on carbon-based fuels are likely to significantly impact the automotive industry, primarily through pressure to increase the fuel economy or reduce the CO_2 emission intensity of vehicles (Fig. 37). OEMs able to produce vehicles with lower emissions will see global market share increase whereas OEMs that produce more GHG-intensive vehicles may have diminished ability to compete in global markets. Apart from the technological developments due to environmental concerns, the investments are likely to also be seen in developing the next generation vehicles such as fuel cell vehicles, hybrid and intelligent vehicles.

Country/Region	Initiatives
European Union (EU)	• Voluntary commitment from the automotive industry to reduce CO2 emissions in passenger cars by 25.0 percent relative to 1995 levels by 2008 • Emission rates are expected to be brought down to a level of 140 g CO2 /km traveled (or 39 mpg) • Depending on early progress, European Automobile Manufacturers Association (ACEA) may extend the target to 120 g CO2/km (or 46 mpg) by 2012
Japan	• Fuel economy improvements in passenger cars to the extent of 23.0 percent relative to 1995 levels by 2010. • Specific targets vary with vehicle weight but extend to 125 g CO2/km (or 44 mpg).
Canada	• The government has proposed a target for improving vehicle fuel efficiency by 25.0 percent by 2010
Australia	• Voluntary commitment to improve fuel economy by 18.0 percent by 2010
United States (California)	• California Air Resources Board (CARB) intends to bring down the GHG emissions from the light-duty vehicle fleet by 17.0 percent in 2020 and by 25.0 percent in 2030

Figure 37: Carbon Constraints Initiatives of the Leading Automotive Markets, Source: Frost & Sullivan

On the global market, the European automotive industry must face particularly such trends and policies defined for the North American and Asian Market. E.g. Japan has been strongly pursuing its domestic action plans to reduce the green house gas (GHG) emissions. The CO_2 emission from Japanese transportation sector accounts for about 20.0 percent of the total CO_2 emissions world-wide. This has been accounted for in a so-called Master Plan which sets specific emission reduction targets for different sectors. The strategies recommended include the wider diffusion of low-emission vehicles (LEVs), improved traffic flow through advances in Intelligent Transport Systems (ITS), and efficient goods distribution. Besides the well established markets such as Japan, North America and Europe, China and India have to be considered by the European industry as well. China is by far the most attractive market for automakers among the Asian countries due to its enormous market potential. Low vehicle penetration in terms of both personal vehicle ownership and public transportation means that an enormous potential is still untapped. Additionally, automotive parts manufacturing units have played a big role in the success of Chinese OEMs in the global arena. With an efficient tier-one, tier-two, and tier-three supplier's base coupled with a high-end technology base, the future Chinese automotive industry is expected to be driven by the advancements made in this segment. India easily is the second most attractive market in Asia with high growth rates in the passenger car segment in particular. The Indian automotive industry in the past has taken up the mantle to comply with the new emission norms and fuel efficiency standards.

The European Union is still the world's largest car-producing area and car market, and its automotive industry is vital to Europe's sustainable development. Europe produces 33% (2003) of the global vehicles, and about 2 million jobs directly depend on automotive industry activities and approximately 0.5 million indirect jobs, which represents an estimated market value of 200 billion Euros. However, the production has decreased in the last few years (36.7% in 1998) and the productivity remains lower than in the USA or Japan. The often unnoticed second tier suppliers to key industrial players are overwhelmingly SMEs which provide employment and economic growth to often rather peripheral regions. They are, however, a significant factor for competitiveness not only for the European automotive industry as up to 70% of components and systems of future vehicles will be provided via outsourcing to the suppliers.

In order the meet the challenges arising from the new markets in Asia and the policies defined worldwide to meet the global demands, the European automotive industry must recognise the world-wide technology trends by incorporating them into their own strategy on the one hand and must actively participate in the market growth by seeking international cooperation even in technology development on the other hand. Among others, light weight design, high efficient engines and efficient use of energy within the vehicles including actively controlling the NVH properties of the car are among the world-wide most important technologies trends to be addressed by the European industry. The project *Green City Car* is contributing to these challenges by addressing a holistic approach of controlled NVH properties of city cars with energy efficient power trains. Thus, Green City Cars results enable relieving system weight (e.g. damping materials) to save energy consumption and finally reducing CO_2 emissions as well as to increase the comfort. The latter is of major importance for the customer acceptance of city cars with energy efficient engines.

The drivers for developing advanced technologies for controlled NVH properties by means of active systems can be summarized as (1) to meet regulations imposed on the automotive industry for the control of emissions, fuel efficiency and safety; and (2) to even gain a competitive edge in application-specific markets of active noise and vibration control. These two drivers are very compelling and not necessarily independent of each other, as the competitive edge driver applies to automotive applications as well as other specific markets although the automotive area is certainly a major market, being the most regulated, and probably as competitive, or more competitive, than other applications thus indicating a potentially easy technology transfer in other applications. The regulations that drive the development of active noise control for automotive markets originate from a worldwide concern for the environment and the issues of clean air and clean water for a burgeoning population that is unfortunately increasing its use of fossil fuels at an even greater rate than the population growth would suggest. The emission of greenhouse gases that has resulted in the unresolved global warming crisis has added to the concern for clean air. These issues respect no political boundaries. Also, political unrest in the oil producing regions with the spread of the unrest via international terrorism has made the situation for fuel economy even more desperate, thereby adding to the drive for greater fuel efficiency, as well as for alternative sources of energy. European emission standards for gasoline vehicles are particularly demanding, as before a new vehicle can be approved for sale in the EU it must meet certain standards for exhaust emissions as specified by EU directives. Included within the emissions regulations are those for carbon monoxide (CO), hydrocarbons, and oxides of nitrogen (NOx), with the 2006 levels down to half or less than half what was allowed in 2001.

For the transport industry, a switch to advanced materials and active system for noise and vibration control would also mean fewer parts and less weight (despite the added mass of the active system). It has been estimated that a 10% weight reduction translates into 4% fuel and emission reduction and that is why weight reduction ranks among the main targets of the transport industry to improve the environment friendliness. This gain can be highly increased when the holistic use of active systems for controlled NVH properties will be proved viable and widely used in the vehicle structure. According to a very conservative estimation of the automotive industry e.g., assuming an average yearly production of 350.000 cars over 8 years and a conventional mileage of 150.000 Km per car, a 10% weight reduction already gives a total saving of 61.000 tons of fuel, which means 200.000 tons less of CO_2 released in the atmosphere. Considering in addition the possibility given by these high performing smart systems obtaining an extended transport components life cycle or a reduction by 50% of the time-to-market for new material integration in the transport supply chain, these numbers altogether illustrate the real potential of environmental hazards savings as well as for strengthening the competitiveness of the European industry.

In dealing with noise as environmental pollution, the industry is going to face new noise directives that will demand noise reduction targets of 10 dB(A) or higher over the next 20 years. On the one hand, the industry will be forced to emphasize the noise aspect in their research and product development to meet the new standards. A key factor will be active noise reduction concepts based on new, intelligent material systems as developed in *Green City Car*. On the other hand, the economic cost of noise to society is estimated to be between 0.2 and 2 percent of the gross domestic product [*COM(96) 540 final*]. Taking the lower estimate, this means an annual financial loss due to environmental noise of more than 12 billion Euros. Several measures ranging from traffic management and regulation to advanced product design are proposed and initiated in order to overcome the noise problem. Among these are intelligent material systems that will have a significant impact. Assuming a share of 10 percent of the financial losses as a potential market for active noise reduction concepts, the annual market volume will exceed 120 million Euros per year. This indicates a substantial trade-off by bringing intelligent material systems into the market and meeting stricter legislation with respect to noise.

Table 3: Potential impact of *Green City Car's* results

	Addressed by *Green City Car*
a) Reduced and rationalised energy consumption	Minimising additional weight of acoustic and vibration control treatments needed in super light structures - hybrid acoustic treatments - lightweight components with active damping - low rolling resistance tyres
b) Reduction in CO_2 & exhaust emissions	Increased customer acceptance of environmental-friendly engines by applying active and passive measures to control noise and vibrations - Noise and vibration control of 2-cylinder engines - low rolling resistance tyres - control of noise and vibration transfer paths
c) Reduced external and interior noise and vibration	Integrated noise and vibration control - advanced lightweight acoustic treatments - low noise tyres - active noise and vibration control

The European added value factors of the *Green City Car* collaborative project include:

- *Green City Car* promotes European automotive industry and research to make efficient use of resources through efficient use of energy and light weight design for enhancement of a significant industry sector employing over 8% of the manufacturing workforce in the EU.
- *Green City Car* is responding to world-wide market-driven technology needs for future vehicles to help challenging the world-wide demand on sustainable and safe transport
- The *Green City Car* technology development will assist the European automotive industry to achieve and secure a leading position in the future.