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Integrated Solutions for Noise & Vibration Control in Vehicles

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Abstract

A strong issue on the development of new vehicles is the weight reduction, required for the reduction of the fuel consumption and the CO_2 emissions. 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 air-borne sound transmission.
In the European FP7 project *Green City Car,* flexible, integrated passive and active solutions are developed permitting noise and vibration attenuation in vehicles equipped with the next generation of highly fuel-efficient two- or three cylinder internal combustion engines (ICE). Among others, shunted piezoelectric patches and electro-magnetic actuation as well as smart Helmholtz resonators are considered. Additionally, dedicated active noise control systems for the control of broadband rolling noise are developed. Besides, *Green City Car* addresses and implements novel damping materials and acoustic treatments as well as design approaches for tyres which are an important acoustic source for exterior and interior noise. 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). Currently, *Green City Car* finished its second year and first results are presented and discussed in this paper.

Keywords: smart structures, active and passive noise and vibration abatement, lightweight design

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1. Introduction

Today's cars represent a complex compromise between contradictory requirements with regard to safety, exhaust emissions, noise, performance and price. However, since it 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, 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. In this regards, the principal vehicle manufacturers in Europe have unanimously agreed to adopt an integrated approach which has as cornerstones the development of more fuel efficient power trains and weight reduction of the vehicle body.

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 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.

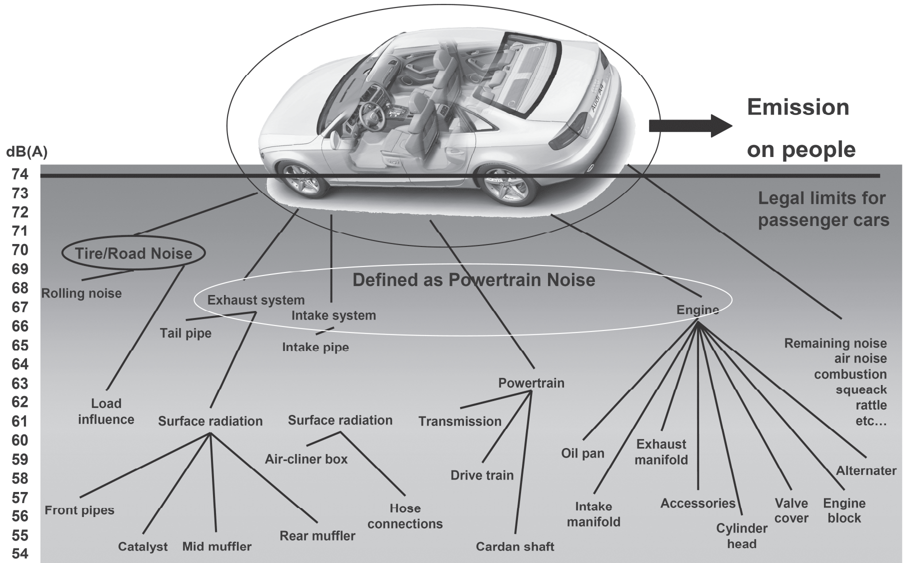


Fig. 1. Components with Influence on Noise (Source: Gerhard)

The scope of this project 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. For automotive applications piezoelectric actuators were of primary interest with respect to price, robustness, temperature range and mechanical loads. The realization of piezo-based fuel injection systems had a major effect on establishing a series-compatible manufacturing technology, thus optimizing reliability, availability and cost of such components. 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. Most relevant to *Green City Car* are concepts dealing with the power train and vehicle body. Regarding the power train, the oil pan - as most radiating component near the engine - was chosen for developing active noise reduction concepts. On laboratory scale, a significant noise reduction could be obtained but with simplified excitation (harmonic excitation). 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. Besides, the isolation of the engine from the vehicle body was investigated in InMAR. A hybrid engine mount has been developed and implemented in a Renault Scenic. Significant reduction on vibrations could be achieved in the main transfer path of the mount. Again, the effect on noise within the car was limited due to new transfer paths perpendicular to the mount as well as multi transfer paths in general. Among others, the high potential of shunt damping techniques (piezoelectric and electro-magnetic) has been proven to be viable concepts enhancing the damping properties of already acoustically treated panels. Active Sound Control using loudspeakers as secondary sources is also well developed in applications where the disturbance is tonal. In particular a number of commercial systems are now produced for controlling sound inside propeller aircraft. Although the principles of controlling engine noise in cars was demonstrated some time ago, its commercial application has been slower than in the aviation field, because of the greater cost sensitivity of the automotive industry. The control of road noise introduces another level of complexity, due to the impossibility to use a well-defined control signal and to the broadband nature of rolling noise. Prototypal systems have been studied in the past at Fiat, using accelerometers on suspension brackets as input signals, but the cost of such systems is not sustainable for the automotive market. Engine Active Isolation mounts have also been investigated and prototype mounts have been developed by car manufacturers. However the weight, complexity and added cost of this technology have prevented its implementation in commercial vehicles.

Therefore, one aim of this project 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.

2. 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. First selected achievements of *Green City Car*

3.1. Application of shunted-piezos on a box test-structure

In view of applying shunt technology to light damped vehicle structures, a test structure (an aluminium box with panels both in steel and aluminium) has been developed. The goal was to find the best position of the piezoelectric patches, to find the best kind of control in order to match the most critical frequencies and to assess the improvement in terms of decrease in dB inside the closed cavity. The analysis has been performed by means of numerical tools so as to validate an analytical/numerical approach. The derived finite element model of the box structure and the corresponding experimental box with the location of the piezo is shown in Fig. 2. Using the validated finite element model the properties of the piezo with synthetic inductor were revised and the needed synthetic inductance developed.

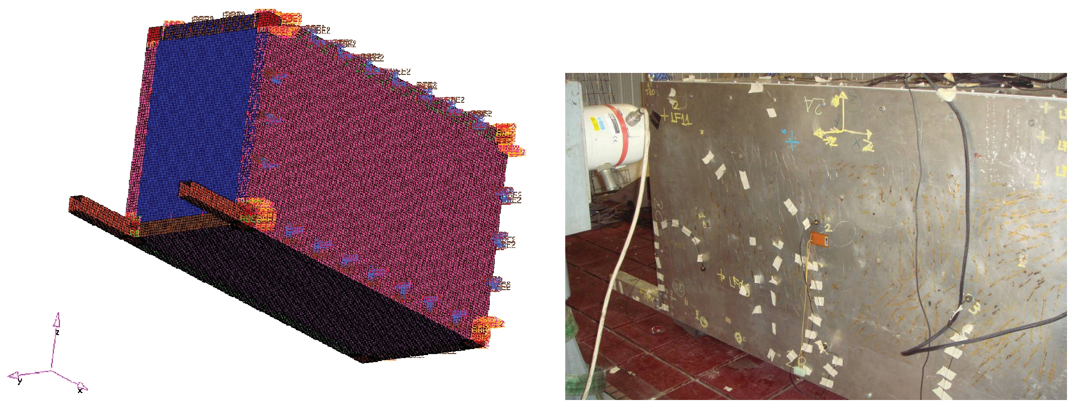


Fig. 2. FE model of the box and set-up of the piezo on the box

The analysis demonstrates that the shunted piezo approach is a suitable countermeasure for light damped structure where the elastic strain energy is concentrated: in this situation the electro-mechanical coupling between piezo and metal parts can be really effective with small change in the increased weight. At the same time, this approach can decrease the noise (measured decrease in the value of the noise peak was -4dB – Fig. 3), provided that the noise peak has been caused by a well-defined panel where the abovementioned conditions can be confirmed.

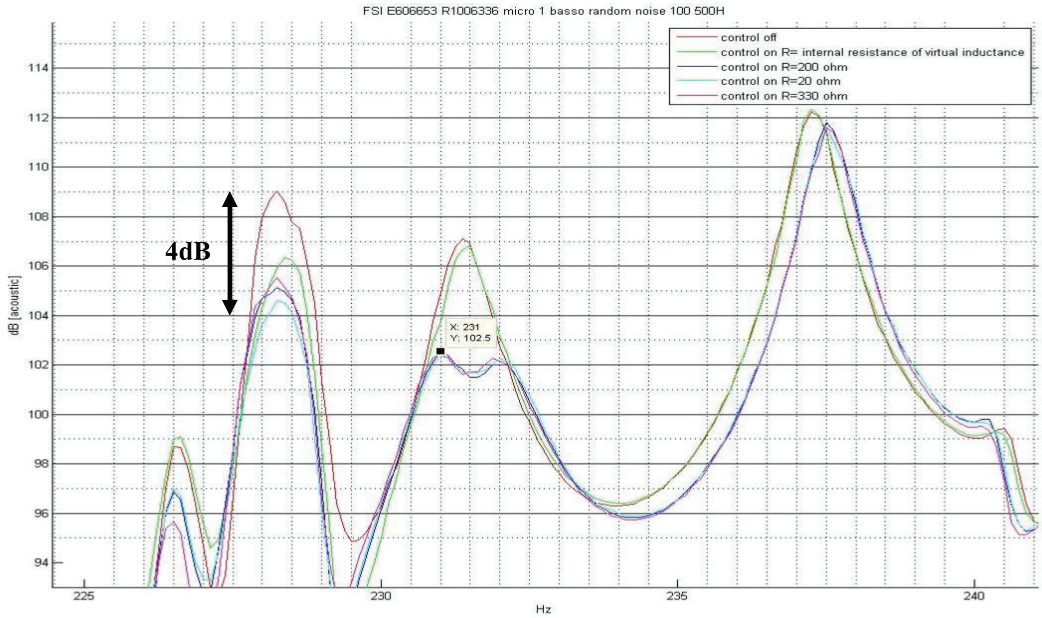


Fig. 3. Noise reduction obtained inside the cavity with a single piezoelectric patch

3.2. Active vibration & noise control by active systems

Furthermore, a concept for active vibration control at a torque arm of a city car's engine mounting system was developed. Based on the application requirements, an inertial mass actuators concept was chosen which can be mounted to various structures with a minimum of design changes. The goal was to implement a force generator based on stiff piezoelectric actuators with a low resonance frequency of about 10Hz, which imposes challenges to the design of the electromechanical systems. Several designs which amplify the stroke of the piezo and transform the stiffness by lever systems have been investigated by analytical estimations and numerical investigations. Afterwards, functional prototypes have been implemented, and characterised experimentally. The results were used for the optimization of the design with respect to the requirements from the city car application scenario.

As shown in Figure 4, the functional prototypes are on a different level of technological readiness. The first two concepts, which base on steel springs, have been realized as an overall inertial mass actuator system. The disk spring concept, which includes fibre reinforced plastic material with integrated actuator elements, is still on the component level. However, this concept promises the most compact and durable solution for an inertial mass actuator, thus it will be further investigated within *Green City Car*. Furthermore, some efforts were spent on shunt damping on panels. Here, the concept of periodically distributed piezo transducers was investigated; however the work is still in basic research stage. Regarding adaptive control systems for active vibration and noise control, improvements to the well-known FXLMS algorithm were elaborated in order to enable the control of disturbances containing a high number of engine speed orders while maintaining a considerably low computational effort. This should alleviate either the implementation on smaller platforms (e.g. microcontrollers) or the utilization of a higher number of control channels.

The application of the inertial mass actuators to an actual car structure involves a mounting on a limited stiffness, in contrast to the laboratory tests where the block force is analysed. With the help of a system level simulation, it was shown, that a reduced stiffness at the mounting points does not have significant influence on the actuator force (Figure 5).

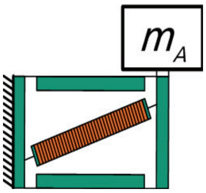
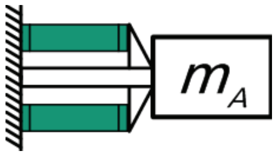
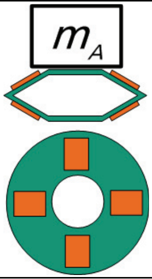
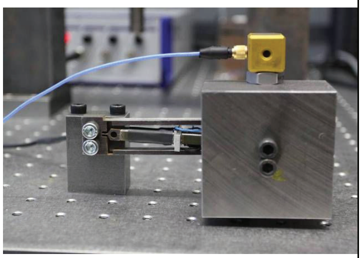
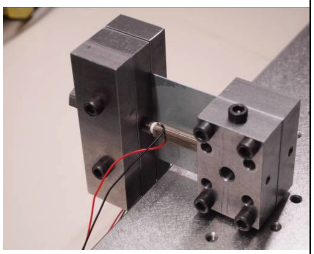
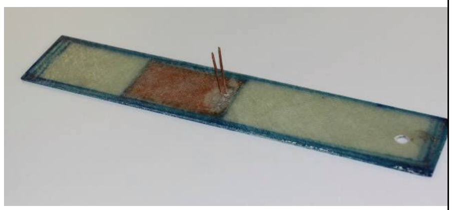
1. Stroke amplified actuator	2. Bending beam	3. Disk spring
		
		

Fig. 4. Developed concepts and the implemented prototypes

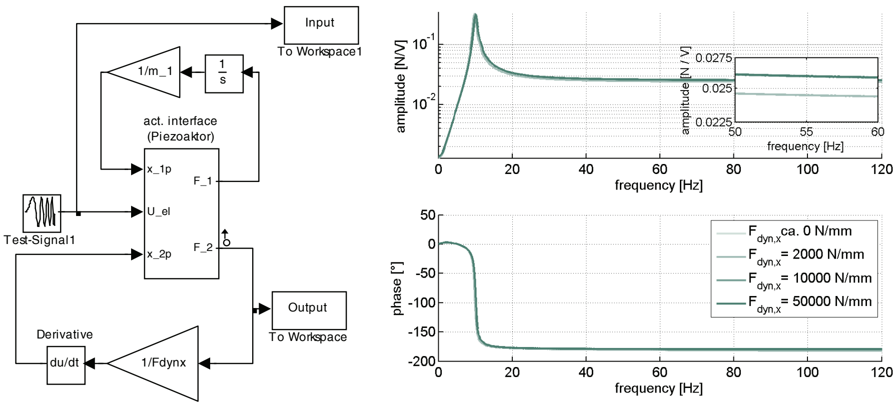


Fig. 5. System level simulation of an inertial mass actuator (left) and results for different stiffness values at the mounting position (right)

3.3. Active Helmholtz Resonators

The functioning of an Active Helmholtz Resonator (AHR) for noise control at an intake system has been investigated. With an AHR a typical Helmholtz resonator is understood where the volume (i.e. spring stiffness of the resonator) can be modified by a loudspeaker.

A simplified theory for the one- dimensional sound propagation in a duct is utilised to investigate the potential performance of an AHR. It turned out that the AHR is able to provide a substantial insertion loss (about 10 dB) even for a 50 % error in amplitude. However the phase accuracy is more critical. This might allow using a CAM signal (i.e. information related to the rpm) from the engine as input to the controller. The AHR was implemented in an experimental setup, where a primary loudspeaker simulates the engine. Based on measured transfer functions an ideal feed-forward controller for the secondary source inside the AHR was designed to the range between 350 and 550 Hz, which was identified as the most relevant frequency range in order to improve the acoustic performance of the intake system. Recoded signals of the sound pressure at the opening of the intake system during a run up are applied to the primary source for a testing. The measured signals were high-pass filtered in order to allow a higher dynamic range for the primary source (cut-on frequency 200 Hz). In addition an inverse filter of the propagation path between primary source and outlet of the intake system was designed to assure that the artificial signal at the opening corresponded to the measured signal. Figure 6 shows an order analysis of the run-up signal used in the experiment without control (left) and with control (right). In addition the Figure shows the resulting reduction as insertion loss (Figure 6 bottom), which is in the frequency band of interest typically between 10 and 30 dB. The results could be improved further by optimisation of the position of the AHR. A key question is still the needed control effort for the secondary source.

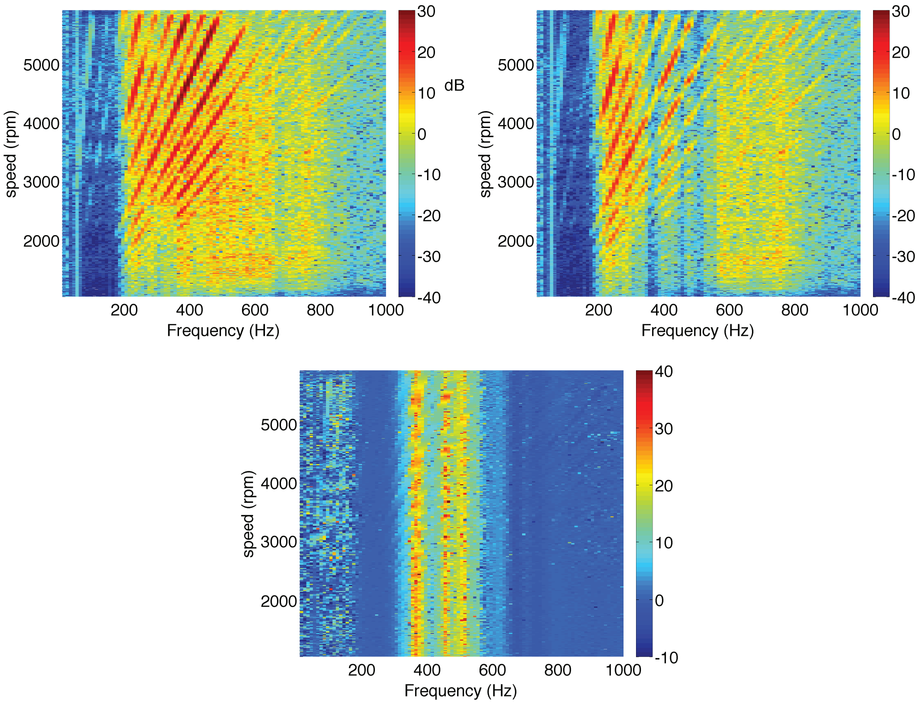


Fig.6. Order analysis of a simulated run-up. Top left: without control, top right: with control between 350 and 550 Hz, bottom: insertion loss (arbitrary reference, no real scale)

3.4. Integrated feed-forward and feedback active noise control system

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 was being investigated that employs feed forward control of engine noise and feedback control of road noise, using a 'modal' error signal, as below (Fig. 7). The principle of modal feedback control is to sum the pressures at a number of error sensors in order to maximise the composite, modal error signal at a specific mode and thus maximise the control of that particular mode when the modal error signal is reproduced by the secondary source. The polarity with which the error signals are summed is determined by their position relative to the nodal lines of the acoustic mode to be controlled. For the source-sensor system shown in Figure 7, in order to control the first longitudinal mode the polarity of the four error sensors in the rear corners of the enclosure is inverted before summation with the outputs of the four error sensors in the front of the enclosure.

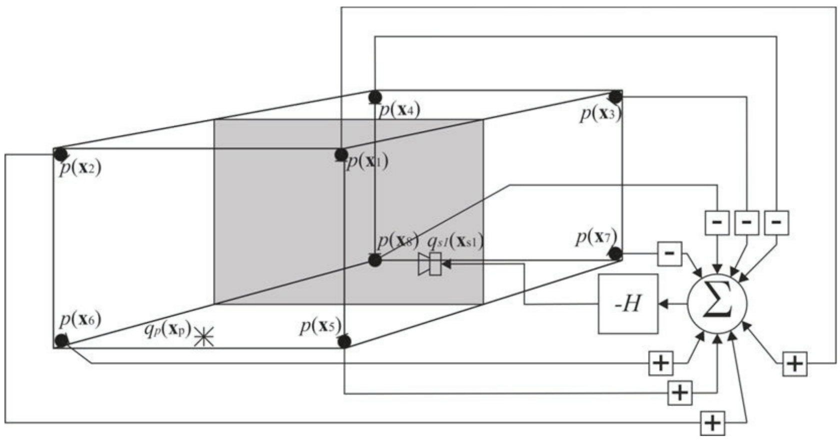


Fig. 7. Modal feedback control system.

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 is investigated. An elemental model of structural-acoustic coupling is 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 (Fig. 8).

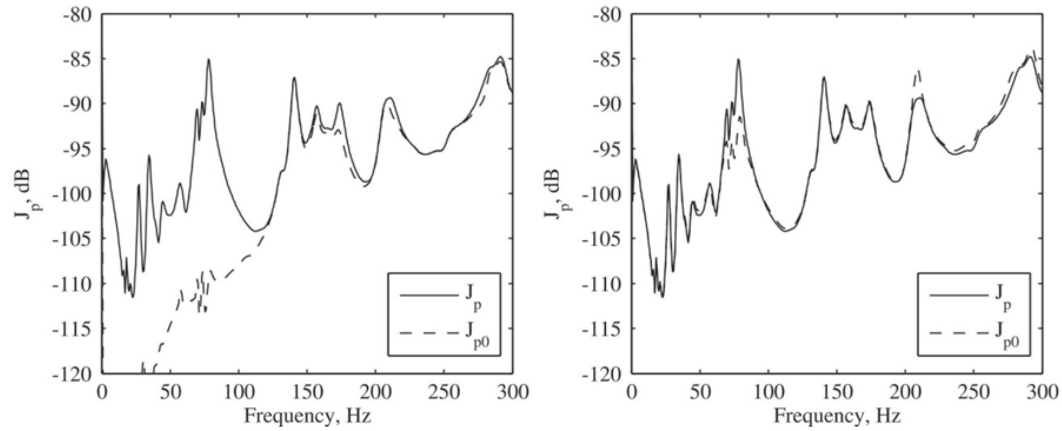


Fig. 8. Left: Estimate of total acoustic potential energy before and after simulated global feed forward control using experimentally measured responses for a single secondary source; right: Estimate of total acoustic potential energy before and after simulated modal feedback control using experimentally measured responses with a single secondary source and a maximum error signal enhancement of 6 dB.

3.5. Concepts for lightweight sound package

Within Green City Car a new type of constrained layer damper has been developed with the best possible compromise between formability, weight, stiffness, and thickness according to the following requirements. The total weight per unit area must not exceed a given maximum value, which, according to extensive benchmarking analysis, can be reasonably considered at 3 kg/sqm.

As constraining layer (top layer), a thin aluminium foil has been chosen due to its highly effective combination weight versus stiffness. The weight per unit area of the middle layer must be as low as possible, in order to help achieve the objective of 20% reduction for the whole vehicle sound package and keep the treatment weight below the benchmarking-derived limit of 3 kg/sqm. The elongation properties at room temperature of the middle layer must be sufficiently high to allow formability (i.e. the material must be sufficiently “stretchable” to avoid cracking during the forming process). This requirement often limits the usage of standard bitumen. The best possible combination stiffness-elongation must be reached to allow high damping by shear stress in the core without compromising formability.

A direct consequence of all the previous requirements is that the middle layer and the constraining layer (aluminium foil) should not be too thick. For formability reasons, the thickness of the aluminium foil should not exceed 0.2 mm and the total thickness of the multilayer should be not more than 1.8-2 mm overall, making it comparable to the typical minimum thickness of single layer damping treatments of city cars.

After extensive research, a new special bitumen-based formulation for the middle layer, in accordance with the above specifications, has been developed. The first prototype layers are at the moment under manufacturing, and comparative analysis is foreseen in order to check the performance of the newly developed constrained layer versus current state-of-the-art solutions.

Furthermore new solutions for the sound package parts in the engine bay have been investigated by developing and testing new materials combining low weight and high acoustic properties (i.e. acoustic absorption and insulation performance). A particularly effective combination has proven to be the double layer made of a special fibre-based material as a lightweight and stiff thermo-acoustic carrier and light-weight foam as an acoustic absorber. All developed materials were prototyped and validated.

In addition, a novel lightweight concept for inner dash insulators has been developed, able to combine locally high acoustic absorption and insulation. This concept has been tested on a single part and in a small vehicle, and has shown similar acoustic performance to conventional heavy insulators with remark-able weight savings.

3.6. Concepts for low noise tyres with low rolling resistance

To optimize the noise inside the vehicle tyres with Conti Seal were built. Conti Seal is an additional air-proof layer in tread applied after tyre curing. Seals puncture in the tread area caused by penetrating ob-jects up to 5mm in diameter and holes are sealed even if the penetrating object becomes dislodged. The tyre with seal has the same high performance under normal driving conditions as non-sealed tyres. The tyres can be mounted on standard rims. The noise levels measured inside the vehicle were lowered by 2-3 dB for low frequencies and up to 5 dB for high frequencies. Additional a foam absorber on the seal was applied as sketched in Fig. 9.

The foam-absorber extremely improves cavity noise performance of tyre as shown in Fig. 10. A reduction of the amplitude at the left cavity frequency of 8.5 dB on rough surface was measured. The left cavity mode completely disappears. The right cavity mode is overlaid by a frequency from the engine so that the effect is not so clear. But even in this case the amplitude is lowered by 4 dB. The solution is very efficient and can contribute to a much better comfort inside the vehicle. The only drawback is the increase of weight of each tyre by 1 kg mass.

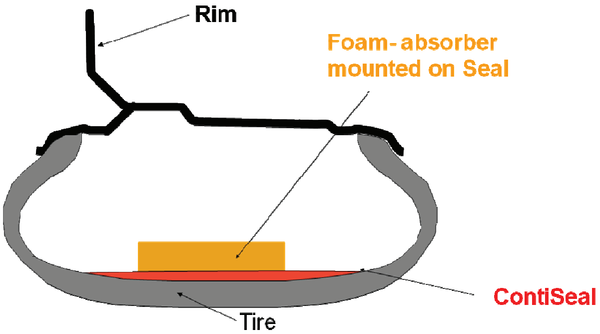


Fig. 9. New design of seal plus absorber

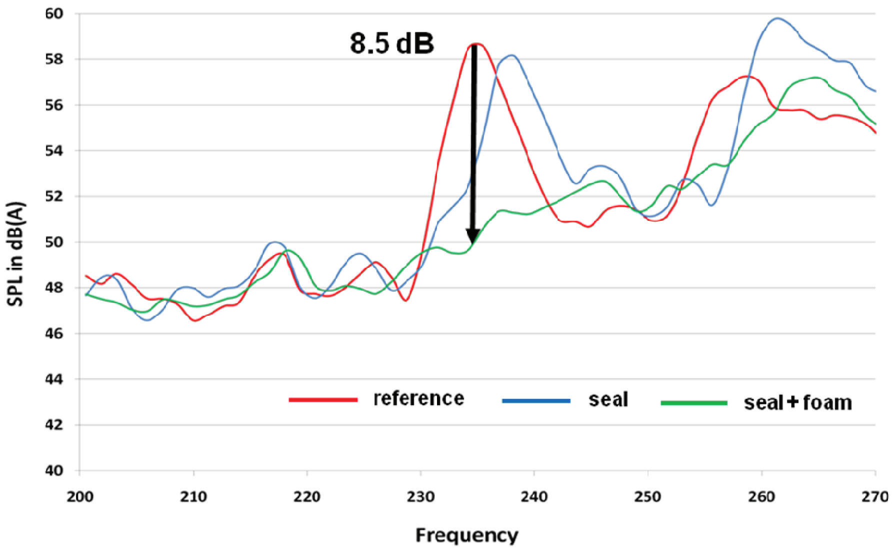


Fig. 10. Interior noise measurements on coarse road – detail

4. Summary and Conclusion

In the first two years of *Green City Car* the focus was on the adaptation and elaboration of enabling technologies to the requirements of city cars. In three work packages specific concepts for suitable actuators, new material systems and innovative tyres were developed and validated on laboratory-scale. With respect to actuating principles, shunted piezo ceramics, concepts for inertial mass actuators and electro-mechanical actuators, adaptive Helmholtz resonators and the associated control strategies were considered. These selected principles were build-up as functional prototypes and validated and simplified structures. It could be proven that all concepts are feasible for the implementation in city cars which is foreseen in the second period. As test cases a lightweight suspension bracket, a torque-roll-restrictor, the intake system, engine components and the cabin has been selected.

Regarding sound package materials, a new type of constrained layer damping treatment based on a thin aluminium foil applied on a new special type of bituminous layer has been developed. This treatment is expected to positively impact on the weight of the final damping package to be made on the demo vehicle, possibly with an added damping performance given by the usage of a constrained layer in the place of a single layer. Moreover, novel acoustic treatments for the sound package have been investigated combining low weight and good thermo-acoustic performance materials for engine bay applications. A particularly effective combination has proven to be a double layer made of a new fibre-based carrier with a lightweight foam absorber, which has been developed, prototyped, and tested. Finally, different designs of tyres for city cars have been developed in an iterative process. A tyre construction was found with both low rolling resistance, good acoustic comfort and an acceptable interior noise, however this construction is not on target regarding the handling performance. In the next phase this tyre design will be further optimized.

Additional information on the project and its results can be found on the project homepage (www.green-city-car.eu) or in the listed references.

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