



# Recent advances in active noise and vibration control

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#### Summary

Noise is a serious form of environmental pollution believed to affect the lives of some 100 million European citizens. The cost of the associated damage is estimated at more than ten billion euros per year. Noise leads to serious health problems, limits the capability to learn, and effects the occupants' comfort and performance in buildings, in vehicles or at work. For instance, the automotive industry is more and more facing the problem of reducing the weight of the vehicle but guaranteeing an equivalent level of comfort in terms of noise, vibration, and harshness (NVH). 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. Thus, active or smart concepts are being increasingly considered for the NVH optimization of vehicles besides advanced passive material systems.

Within the LOEWE-Center AdRIA (Adaptronics – Research, Innovation, Application), a large interdisciplinary research project funded by the German federal state Hessen, and at the Fraunhofer LBF advanced noise and vibration abatement concepts were being developed and demonstrated. Among others, NVH abatement in vehicles and noise abatement in buildings is being considered. As underlying principle for noise reduction concepts, active structural acoustic control (ASAC) is primarily being considered for controlling the structural vibration of the sound radiating structure or by controlling the structure borne sound path. This paper will present an overview of the most recent concepts and results of the LOEWE-Center AdRIA such as active vibration control at engine mounts and smart windows. Examples presented will include active mounts, inertial mass actuators, shunt technologies with piezoelectric ceramics and smart Helmholtz resonators.

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## 1. Introduction

Since the 1990s, there has been an enormous growth in smart structures technology. Several fields of study benefit from this development, such as space vehicles, aircrafts, railway and automotive systems, robots, heavy machinery, medical equipment, etc. A wide range of applications include noise and vibration suppression, damping increase, structural health monitoring, energy harvesting, etc. A smart structure typically consists of a host structure, actuators and sensors, a microprocessor that analyzes the signals, a control law to change the characteristics of the structure and integrated power electronics. More importantly, a smart structure has the ability to adapt its properties according to external stimuli in a controlled manner. Several types of structures, actuators, sensors and control laws have been studied and published in the past. In this paper recent concepts for NVH abatement in vehicles and for noise

abatement in buildings developed within the German LOEWE-Center AdRIA will be presented.

The research on noise and vibration control for vehicles addressed by the LOEWE-Center AdRIA was motivated by the challenge to reduce the vehicle weight but guaranteeing an equivalent level of comfort in terms of noise, vibration, and harshness (NVH). 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. Besides advanced passive material systems, active or smart concepts are being increasingly considered for the NVH optimization of vehicles. However, to overcome contradicting requirements traditional design and material choices must be revisited. In this context new technologies in the fields of smart materials and active control provide potential solutions although they have mainly been proved in the laboratory.



Figure 1. Project structure and timeline of the LOEWE-Center AdRIA

Besides, the acoustic shielding of ambient noise for large public buildings such as hotels, hospitals, airports, or conference centers, which are often situated near airports, major roads, and railway lines, is very important and in many cases difficult to handle with classic passive methods as well. Double-glazed or triple-glazed windows and sound proofing materials are able to reduce sound immission effectively above 1000 Hz. In the low frequency domain passive sound proving methods are often inapplicable because they lead to a significant increase in weight and cost exceeding the physical and financial limitations of the construction in many cases. In this context, advanced noise abatement concepts were developed using Active Structural Acoustic Control (ASAC) concepts.

# 1.1. The LOEWE-Center AdRIA

The "LOEWE-Zentrum AdRIA" (Adaptronics – Research, Innovation, Application) [1] was a large interdisciplinary research project located in Darmstadt, Germany, that was funded by the government of the German federal state Hessen. This project aimed at creating and sustainably implementing an internationally leading research center for adaptronics (i.e., smart structure technology) in Darmstadt. Within this center, the Fraunhofer LBF cooperated with 22 research groups from six different departments of the TU Darmstadt, and with one department of the Hochschule Darmstadt from 2008 to 2014.

The scientific objective of the LOEWE-Center AdRIA was to increase the marketability of devices for active noise and vibration control by means of a balanced mixture of basic research, applied research, and industrial applications within the three so-called application scenarios "adaptive car", "quiet office", and "adaptive tuned vibration absorber" (see Figure 1). This is achieved by simplifying and standardizing the design and implementation process of smart structures, by tailoring innovative transducer materials and novel electronics and control concepts, and by incorporating robustness, reliability, and recycling aspects.

This variety of topics requires a rather interdisciplinary approach with many different areas of research cooperating within the project. These different areas of research are organized in nine so-called technology areas (see Figure 1) with the following topics and titles: "materials", "simulation", "sensors & actuators", "embedded systems", "control strategies", "adaptronic systems", "structure health monitoring", "rapid prototyping/rapid manufacturing methods" and "manufacturing".

# 2. Noise and vibration abatement in vehicles

The potential for active noise and vibration control in automotive applications has been demonstrated already some time ago. Extensive research was committed to active noise control (ANC) with loudspeakers [2], and those systems have been industrialized in the last years also in the automotive industry. Also the principles of active vibration control (AVC) and active structure acoustic control (ASAC), which utilize dynamic active forces for disturbance compensation, have been investigated. Mainly, the transmission of vibrations from the engine has been tackled by active systems, in some cases also in combination to ANC systems [3]. There are some main principles for the implementation of the actuation, like active absorbers or inertial mass actuators for inducing point forces [4] or active mounts for enhancing isolation between two subsystems [5].

Within the LOEWE-Center AdRIA a NVH abatement system for a middle-class vehicle with a four cyclinder engine was developed and implemented. The system is combining an active engine mount with four inertial mass actuators (IMA) based on electrodynamic principles. The active engine mount is installed at the passenger engine side and replaces the conventional hydro mount. The IMAs are located at the left engine mount, the two swivel supports and at the trunk lit.



Figure 2. Actuator and sensor placement

### 2.1 The active engine mount

Existing active mounting systems often utilize a serial arrangement of an actuator and a passive elastic coupling element. However, such a serial arrangement of the actuator with the suspension spring carries the disadvantage that the actuator is fully exposed to the static loads. This usually results in both, an unnecessarily large actuator and high power requirement. A smart arrangement of the suspension components that divides the loads into two separate paths enables the decoupling of the actuator from the static load. In the case of the presented engine mount (Figure 3), the decoupling is realized by means of a serial arrangement of the actuator and a viscous damper. The counteracting force is introduced to the structure through the viscous damper whose dynamic stiffness increases as the frequency rises. The majority of the static and quasi-static loads are carried by a second elastic coupling element that keeps the engine in its position. This ensures that almost no static and quasistatic forces are transmitted to the actuator.

In case of actuator failure the passive isolation effect remains. This allows for both, minimizing the actuator loads and transferring the dynamic counterforces to the vehicle body efficaciously. Since piezoelectric actuators feature the capability to introduce high forces but only little strokes, the use of a stroke amplification mechanism is envisaged. The active mount is designed to compensate the dynamic forces in the vertical direction only, since the excitation in this direction dominates. However, the extension to other directions is basically feasible.



Figure 3. The implemented active engine mount

# 2.2 The control concept

An adaptive control concept is used to generate an appropriate signal for the actuator. In order to reduce or synthesize harmonic signals the use of feed forward control concepts is common. The Filtered Reference Least Mean Squares Algorithm (FxLMS) is well known [6] and implemented in the present case. In order to compute the control signal the actual rotational speed is measured. Based on this information a synthetic and harmonic reference signal is generated by an oscillator. Knowledge of the rotating system's angular position is not required. The filter weights are adapted according to the gradient based FxLMS method, which requires information about the dynamic behavior of the system to be controlled. This system identification can be easily realized by means of adaptive FIR-filters [7]. For experimental testing the control algorithm was implemented on a rapid control prototyping system. However, the algorithm has been successfully tested on embedded control platforms in previous studies, too [8].

# 2.3 Results

For comparison of the different configurations, measurements were taken for the original configuration with the serial mount, for the implemented NVH abatement system in the uncontrolled and controlled state. Accelerations were measured at the chassis side of the engine mount whilst the sound pressure was measured in the passenger cabin at driver's ear position. The acceleration and sound pressure signals were collected by a LMS data acquisition system. In Figure 4 and 5 the sound pressure data measured during an engine run-up is shown for the uncontrolled and controlled configuration.



Figure 4. Spectrograms of the sound pressure at the driver's ear- uncontrolled configuration



Figure 5. Spectrograms of the sound pressure at the driver's ear- controlled configuration

The active mount was designed to have a comparable dynamic stiffness to the serial mount. By comparison of the serial engine mount with the uncontrolled active engine mount the difference of the amplitude is mostly between -5 and 5 dB. This indicates that the passive behavior of the serial mount in the vertical direction is comparable to the behavior of the developed active mount in passive condition (see Figure 6).

Because of the fact that the second engine order represents the dominating harmonic distortion, the controller is adjusted to reduce the disturbance of this particular order. Thus, the second order in the acceleration signal is significantly reduced in the active condition. In the experiments only one active mount is implemented. However, the engine is attached by several mounts. Therefore the vibrations are transmitted into the passenger compartment by a variety of transfer paths where they are emitted as airborne sound. On this account it is comprehensible that better results are achieved at the car body vibrations than at the interior sound pressure. Nevertheless using the sound pressure as error signal significant reductions can be obtained.



Figure 6. Reductions of the second engine order – sound pressure in the cabin

These results could be enhanced by the use of more than one active mount. To illustrate the influence on the second order the order cuts for the car body vibration and the sound pressure measured during the engine run-up are shown in Figure 6. With respect to the serial mount, a significant reduction of the acceleration of the second order amplitude up to 20 dB is achieved by the active mount. Referring to the sound pressure, noise reductions up to 10 dB are achieved. The improvement is highlighted by a green colored background.

#### 3. Noise abatement in office buildings

Within the LOEWE-Center AdRIA a special acoustic test bench was build-up to investigate the noise transmission through simple metal panels as well as double-glazed windows (see Figure 9). Among others, shunt damping, active Helmholtz resonators and fully active systems were considered.

#### 3.1 Shunt Damping

A reduction of the mechanical vibrations is possible by means of shunt damping technology. By applying transducers such as piezoceramics a conversion of mechanical to electrical power can be achieved. This energy can either be dissipated by a resistance or buffered in an electronic resonant circuit. The first increases the damping of only lightly damped structures whereas the latter behaves like a mechanical tuned vibration absorber. Advantages of vibration reduction with an electronic resonant circuit (RL-shunt) are that no electrical energy is used to drive an actuator, the small complexity and costs, an easy adaptability as well as the good integration potential. Depending on the application and the value of the inductor either a passive component or a synthetic inductance, realized with an operational amplifier circuit, can be used. The latter gives the possibility to easily adapt the inductance and thus the tuning frequency during operation.

This concept was applied to a flat panel representing, e.g., facades or window elements. The experimental measurements confirmed the high potential of shunt damping for slightly damped structures (Figure 7). In this test case a reduction of the frequency response function of 5 dB can be observed at the tuning frequency (1650 Hz) without any overspill when applying an electrical resistance of 1 k $\Omega$ . In this case the shunt damping acts like a highly damped mechanical absorber. When applying only a small resistance of 1  $\Omega$  the behavior is more like a slightly damped absorber with much higher vibration reductions (12 dB) but with its typical secondary resonance frequencies.



Figure 7. Shunt damping of a flat panel

#### **3.2** Active Helmholtz resonators

Helmholtz resonators (HR) are well-known measures for narrow band passive reduction of airborne sound [9]. However, due to, e.g., chang-

ing environmental conditions adaptable systems are required for an optimal reduction of sound energy. Designing the HR as a semi-passive system it is possible to adapt the effective frequency band of the HR to the changing environmental conditions. As a semi-passive system the adaptable HR benefits of lower energy consumption for the dissipation of sound energy compared to active systems. In this manner it is only necessary to spend energy for changing the tuning frequency. This tuning process can be accomplished by changing either the geometry of the neck or the volume of the body.



Figure 8. Impact of one and four HRs on the radiated sound power with a volume displacement excitation

The impact of adaptable HRs on the sound transmission of the double-glazed window was investigated using FE-simulation of the acoustic test bench. The system simulation was complemented with one to four HRs placed in the corners of the air gap between the two glass plates. The resonators were considered adaptive and are controlled using the phase difference of the sound pressure governing in the interspace of the two glass plates and inside the HR's body. For the excitation of the system model it is possible using force in analogy to the real test-rig or volume displacement excitation on 1 m<sup>3</sup> inside the acoustic cavity inside the acoustics demonstrator. The calculated effect is shown in Figure 8 for the latter. It can clearly be seen, that resonators have a positive effect on the sound transmission through the double-glazed window above the first eigenfrequency.

#### 3.3 Fully active system

Furthermore, a double-glazed window has been set-up again to improve the performance of the ASAC approach. The experimental set-up is shown in Figure 9. The double-glazed window is mounted on the acoustic demonstrator and can be excited either by a loudspeaker or by an electrodynamic shaker. A microphone outside the box is used as error signal for the control algorithm. As actuator for the ASAC approach just one single piezoelectric patch was bonded to the outer pane. For test purposes the window was excited with a rotary machine noise using the loudspeaker inside the box. As shown in Figure 10, the vibrations at two critical frequencies were reduced by more than 20 dB. However, this set-up needs to be extended to multiple actuators and error sensors based on accelerometers (e.g., piezoelectret foils) in view of practical implementation and to cope with arbitrary noise sources (white/pink noise).



Figure 9. Acoustic test bench with experimental set-up



Figure 10. Sound pressure level of the error microphone when excited with a rotary machine sound

#### 4. Conclusion

Several approaches to implement NVH abatement systems into automobiles and windows have been investigated. Experimental results from the laboratory as well under real-life conditions are promising and prove the applicability of the concepts. On-going research mainly deals with issues of system integration. The integration also includes testing of the embedded solutions by modern development tools like hardware-in-the-loop in order to align the development of the active vibration control systems with widely established development processes for mechatronic systems.

More individual aspects and detailed results of the presented research can be found, for example, in the papers [10-12].

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