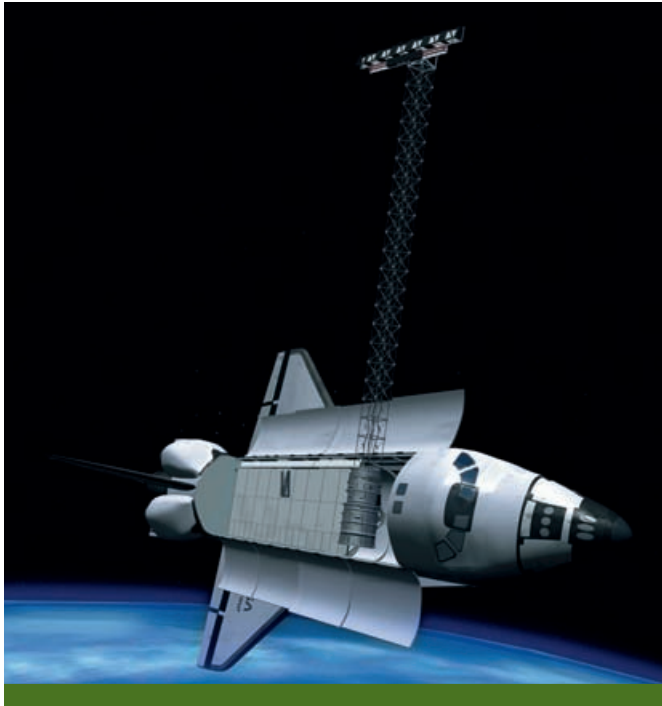# Active Noise and Vibration Reduction

Passive measures for reducing noise and vibration or for ensuring optimal structural performance have reached certain limits. For this reason, active techniques are becoming increasingly important. As funds have become available to pursue research in this area, terminologies have been introduced to define the field of study. The terms smart structures, intelligent structures, adaptive structures, active structures, adaptronics, and structronics all belong to the same field of study. Once developed for aerospace applications like the orbital truss structure used in the shuttle radar topography mission, active noise and vibration reduction is today used in modern automotive engineering.

1. Smart Structures

All these terms refer to the integration of actuators, sensors in structural components, and the usage of some kind of control unit or enhanced signal processing with a material or structural component (**01**). The goal of this integration is the creation of a material system having enhanced structural performance, but without adding too much mass or consuming too much power. Due to its nature, the field of smart structures depends on inter-disciplinary research since numerous disciplines (e.g. material science, applied mechanics, control theory, etc.) are involved in the design of a smart structure system solution. The materials used in smart structures often have interesting and unusual properties. Electrostrictive materials, magne-

tostrictive materials, shape memory alloys, magneto- or electrorheological fluids, polymer gels, and piezoelectric materials, for example, can all be used to design and develop structures that can be called smart. However, the materials themselves are not smart. "Smartness" refers to the exploitation of material properties to better serve a design function than would be possible through conventional structural design. In the following, two active techniques are presented, to demonstrate the use of smart structure systems in production and automotive applications. Starting with vibration isolation, the main concept of active techniques applied to rigid body dynamics is introduced. In the followed section the application of an active vibration control to the interior of a car body is presented.

2. Vibration Isolation

Isolating a piece of delicate equipment from the vibration of a base structure is of practical importance in a number of engineering fields. For instance, in industry and research the quest for tighter production tolerance and higher resolution places stringent requirements on the environment. In the majority of cases, the base is flexible and vibrates with an unpredictable waveform which has a broadband spectrum. Passive anti-vibration mounts are widely used to support the equipment and protect it from severe base vibration. However, conventional passive mounts suffer from the inherent trade-off between poor high frequency isolation and amplification of vibration at the fundamental mounted resonance frequency. Generally the best isolation performance is achieved by using an active system in combination with a passive mount, where the fundamental resonance can be actively controlled without reducing the high frequency performance.

In the last decade various strategies for active vibration isolation have been discussed, including feedforward and feedback concepts for systems under periodic as well as random vibrations.

Especially decentralized velocity feedback control was employed, whereby each electro-dynamic actuator is operated independently by feeding back the absolute equipment velocity at the same location. They obtained good control and robust stability both experimentally and theoretically for multichannel control systems.

To demonstrate the performance of an isolation system, an experimental setup as shown in **03** is considered. The setup consists of a heavy base plate which is suspended on six springs. In order to minimize the interaction between the vibration isolation system and the spring-mass-system of the experimental setup, the mass of the base plate (2 t) is chosen to be much larger than the mass of the vibration isolation system (30 kg). The isolation performance can be determined by constructing a transmissibility curve. Transmissibility is simply the response of the isolation system divided by the excitation (in the frequency domain), where the response and excitation have been measured with accelerometers. The excitation of the base plate is realized using a conventional loudspeaker which is connected to the base plate via a stinger. The output from the function generator is first amplified using a conventional HIFI amplifier before being used to drive the loudspeaker. The rigid body eigenfrequencies of the spring supported base plate are between 1.44 and 2.88 Hz. **04** depicts the measured transmissibility curves for the passive and active isolation systems, respectively. Here, the active system is realized using a decentralized analog feedback controller. It is seen that almost over the entire frequency range a significant reduction in the transmissibillity curve is obtained using the active system. At frequencies above 40 Hz, noise appears in both
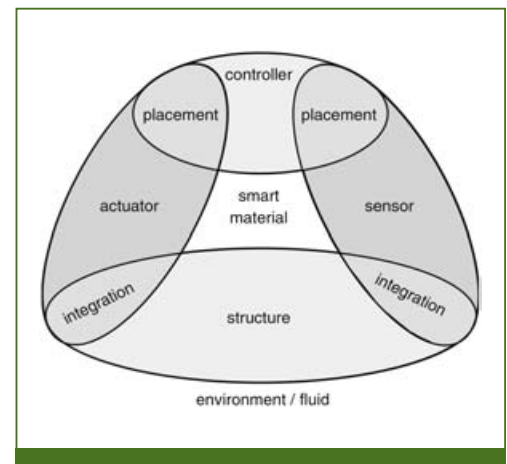

Integrated smart structure.

Active vibration isolation system.

SUMMARY

Die akustischen Eigenschaften von technischen Produkten spielen eine immer bedeutendere Rolle. Insbesondere im Automobilbau sind die Anforderungen an das vibroakustische Verhalten durch Leistungssteigerungen, kompaktere Bauweisen und strengere gesetzliche Vorgaben weiter gestiegen. Aktive Schwingungsregelung zur Reduktion oder gezielten Beeinflussung des abgestrahlten Schalls gewinnt dabei mehr denn je an Bedeutung. Während passive Maßnahmen wie Schwerematten und Antidröhnfolien Schwingungen im mittleren und oberen Frequenzbereich effektiv dämpfen, führt deren Einsatz im niedrigen Frequenzbereich zu einer erheblichen Gewichtszunahme. Aus ökonomischen und ökologischen Gesichtspunkten strebt der Fahrzeugbau jedoch eine leichtere Bauweise an. Diese Anforderung bedingt die Einsparung schwerer Dämmmatten und führt häufig zu einer Verschiebung der Eigenfrequenz der Struktur in einen niedrigeren Frequenzbereich. Aus rein mechanischer Sicht führen die Ziele einer leichten Bauweise und eines Produkts mit guten akustischen Eigenschaften unter Verwendung rein passiver Maßnahmen zu sich widerstrebenden Konstruktionsvorgaben. Aktive Maßnahme und die Verwendung von so genannten Smart-Structures sind hingegen in der Lage diese Lücke zu schließen.

Acoustic properties of modern engineering products have gained more and more in importance. Especially in automotive engineering we have high requirements to the vibroacoustical behavior of each component and the total system. Active control techniques for isolating or reducing the structural vibrations are starting to play a major role in this field of applications. While passive techniques like foam mats can be very efficient in the middle and high frequency range, they lead to a significant increase in weight, when applied to reduce vibrations in the low frequency range. But especially in automotive engineering light-weight constructions are desired. This yields two implications. On the one hand the resonance frequencies of the structure are lowered and on the other hand heavy coatings should be reduced. From mechanical point of view this demands are contradictory. However active concepts and so-called smart structures are able to close this gap.
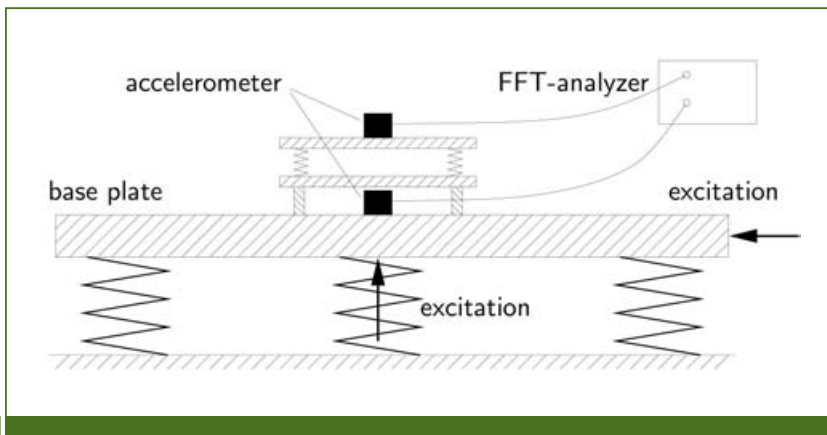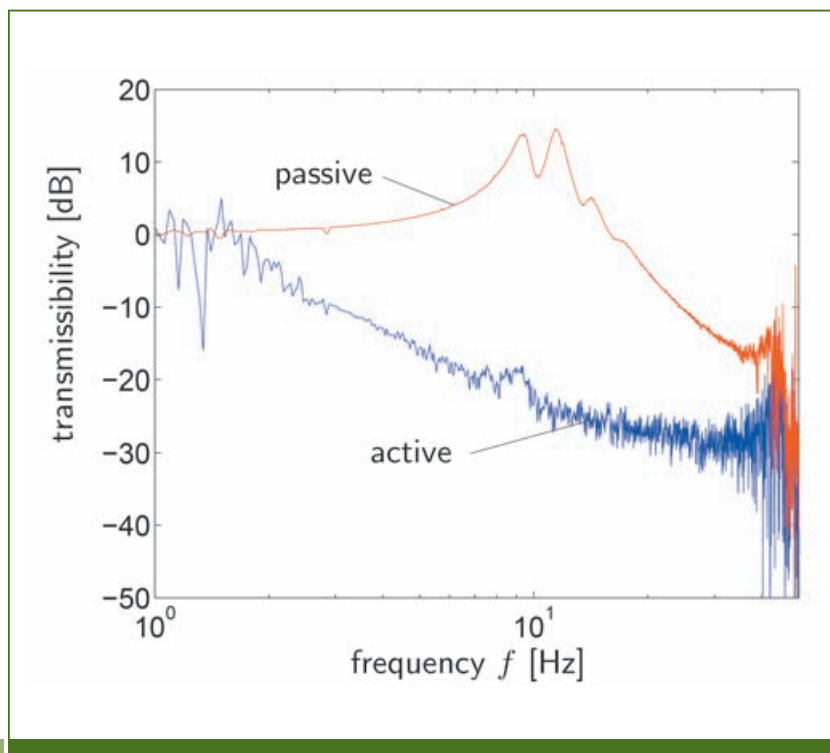
03

Experimental setup for testing of an active vibration isolation system.

04

Measured vertical transmissibility curves for the passive and active vibration isolation system.

curves. This is due to the dynamic behavior of the actuators.

3. Active Vibration Control

Structural vibrations of a car body are caused by the engine, the wheels, the chassis, and the airflow. The vibration propagates from its source through the entire car body (**05**). Since car bodies are made of metal with low material damping, the sound propagates with high efficiency. Vibration of the roof, the doors, and the floor panels causes the radiation of sound into the interior of the car. The sound radiation can be reduced by covering the surface of the structure with foam mats or by applying active vibration control concepts.

One of the earliest studies of active vibration control was completed by Swigert and Forward [4]. They conducted a theoretical and experimental study that involved electronic dampers. In that study, a system of electromechanical transducers made from lead zirconate titanate (PZT) were implemented to control the mechanical vibration of an end-supported mast. The output signals from the sensors were amplified and appropriately shifted in time to provide control inputs for actuators positioned symmetrically on the surface of the mast. Bailey and Hubbard [6] developed the first smart structure using polyvinylidene fluoride (PVDF). The PVDF was used as an active element for active vibration control of a cantilever beam. In a later study, Fuller et al. [6] described a systematic approach for active control of vibration. They summarized the principles underlying active vibration control and its practical applications by combining material from vibrations, mechanics, signal processing, and control theory. Today, two main approaches exist in vibration control: feedforward and feedback control. The feedforward approach makes use of adaptive filtering methods such as x-filtered LMS algorithms. The main advantages of these control systems are that no model of the structure is needed and that they can be employed at high frequencies. The advantage of the feedforward controller for high frequencies is a result of its less sensitivity to phase lag and the sensor position. The reference sensor used for feedforward control is located up-stream to the incoming wave. Therefore the optimal feedforward control system reacts to the disturbance without time delay as opposed to a feedback control. The major drawback of the feedforward method is that a reference signal is required, which is somehow correlated with the disturbance.

Feedback methods can further be divided into two parts: active damping and model-based control techniques. In the active damping approach, sensors and actuators are located at the same position, which is called a collocated setup. It can be shown that collocated sensor/actuator pairs results to control stability since the root

locus never leaves the left plain of the root locus plot. For non-collocated sensor/actuator pairs so-called pole-zero flipping may lead to instability. To prevent pole-zero flipping the prediction of all imaginary zeros within or near the bandwidth of the control system is required. Feedback control is guaranteed to be stable if ideal sensors and actuators are used. The active damping method has the advantage that it does not require a model of the structure. However, it has the major drawback that it works only near structural resonances.

There exists a large variety of model-based feedback methods, including LQR, H-Infinity and modal feedback methods. Especially modal feedback control has been successfully implemented for the reduction of plate vibrations. The modal parameters for plates can be determined using analytical solutions to the governing plate equation or by using finite element (FE) calculations. For structures with a complex geometry, such as a car body, an analytical solution does not exist, and even a FE calculation is complicated and time intensive. As an alternative, an experimental modal analysis can be used to extract modal parameters, such as eigenfrequencies and mode shapes, from measured data. The mode shapes contain the necessary information for the layout and placement of sensors and actuators. After the actuator and sensor positions and dimensions are fixed, modal input and output matrices of a state-space model can be calculated. These matrices are used in a modal state-space controller. Errors caused by slight nonlinearities of the structure or by the modal analysis curve fitting procedure result in a discontinuity in the mode shape. Therefore, a direct evaluation of the input and output matrices is not possible. In such cases the mode shapes have to be approximated by polynomials or cubic splines. Since the input and output matrices are used to create a real time modal filter, the control law is formulated in modal coordinates.

The proposed modal concept was implemented on the centre panel within the passenger compartment of a roadster car body, as shown in **06**. In **07**, the experimental set-up is depicted. The set-up consists of two independent circuits. One circuit is used for the vibration control of the car body whereas the other circuit is used to monitor the resulting vibration.
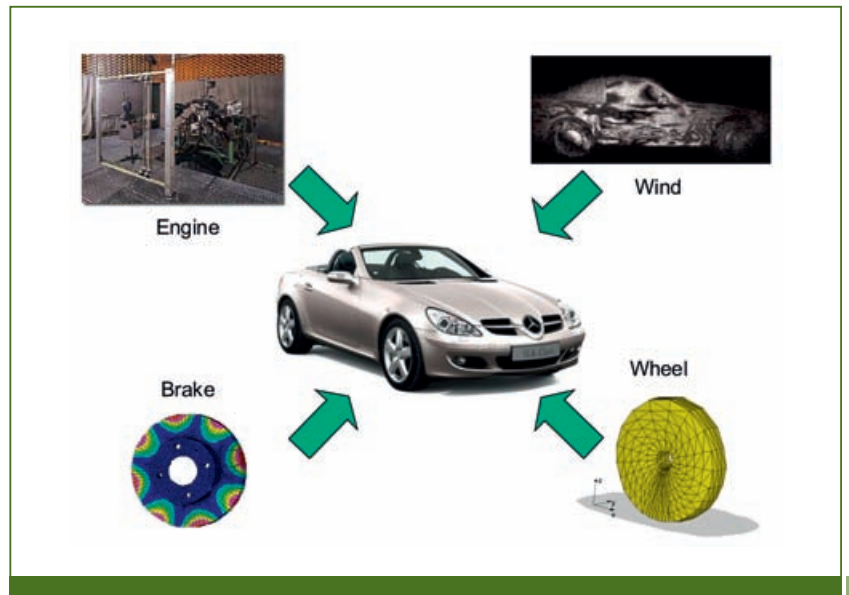

Examples of Vibration Sources in a Car.

08 shows the sensor and actuator layout on the front side of the centre and floor panel. Since the actuator on the back side of the centre panel covers almost the complete area of the panel the sensors are bonded on the surface of the actuator. Nevertheless, there are no collocated sensor/actuator pairs. The collocation of sensors and actuators is not required since the sensor signals are not fed back directly to the actuators but they are
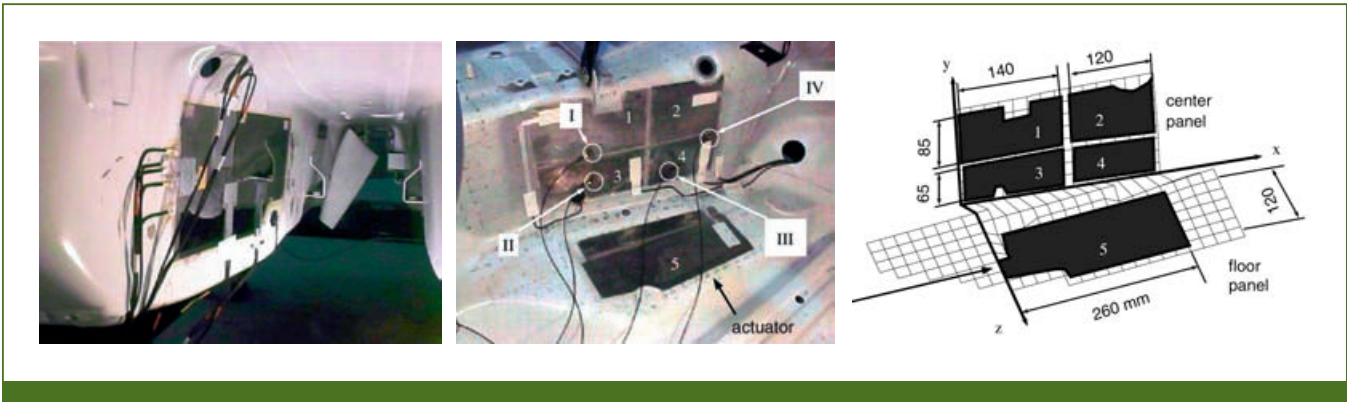

Car body in white for active vibration control (AVC).
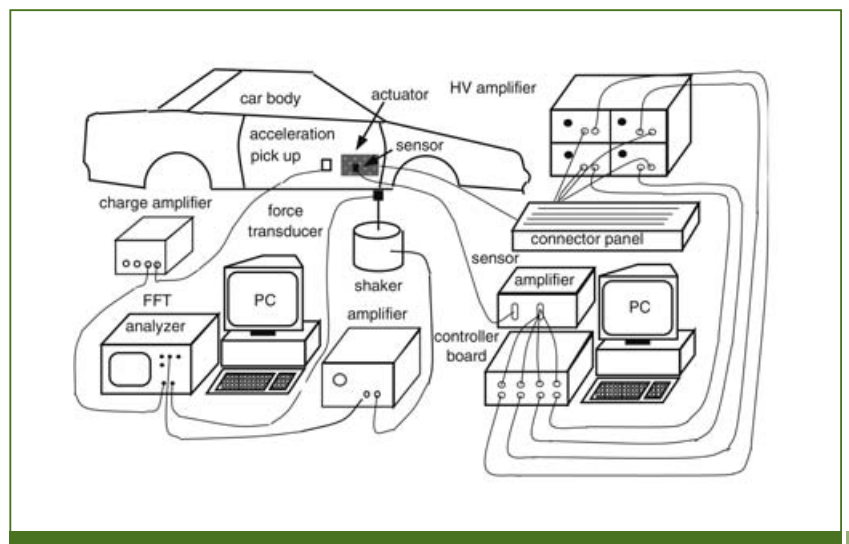


Setup of the controlled car body.

08

Centre and floor panel with PVDF actuators and collocated sensors inside passenger compartment.

filtered to achieve modal displacements and modal velocities. In order to protect the sensor signals against the electro magnetic field of the actuator, the sensors are covered by an aluminum foil and connected with shielded cables to the signal amplifier. In the evaluation circuit the resulting vibration is monitored with four acceleration sensors. Measuring the excitation force and the structural response enables the calculation of frequency response functions (FRFs). **09** shows the four measured FRFs for the controlled/uncontrolled centre panel of the car body. As a result of the implemented modal controller, the peaks at the resonances

(196 Hz, 281 Hz, 457 Hz and 500 Hz) of the controlled modes are significantly reduced. Additionally, the vibration amplitudes of other modes, which are not explicitly included in the control concept, are also decreased. This can be explained by the shape similarity of the controlled and uncontrolled mode shapes. Nevertheless, not all vibration amplitudes are equally reduced for a particular actuator layout. Only those modes for which a sensor/actuator layout has been tailored, will be effectively controlled. • *Lothar Gaul*

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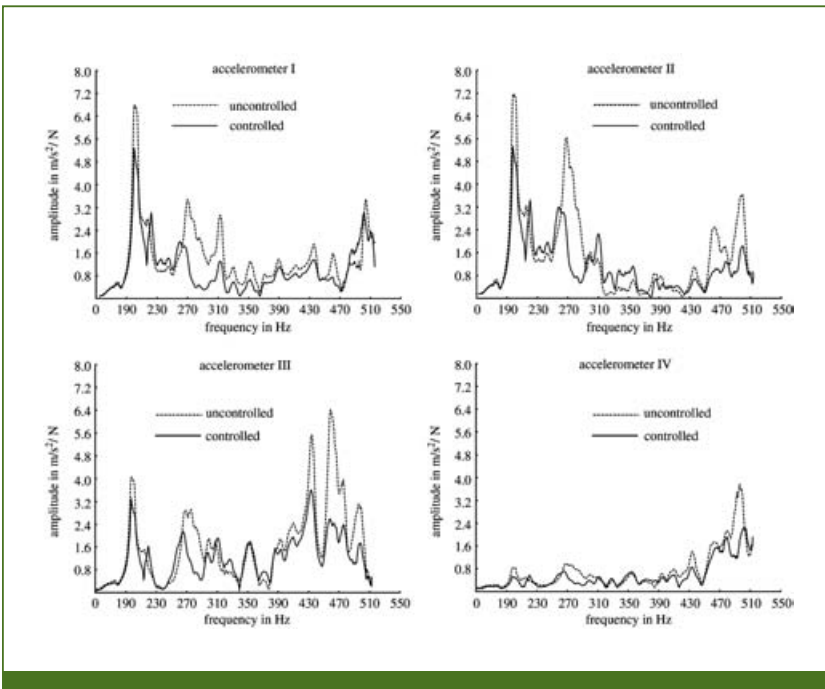
*Measured frequency response functions
for the centre panel of the car body.*

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