Smart Materials and Active Noise and Vibration Control in Vehicles

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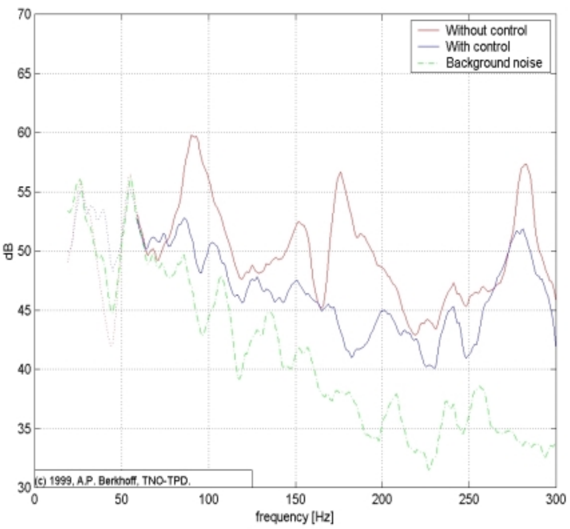
Results are presented for the reduction of sound radiated from a structure using different control methodologies. Two approaches for active structural acoustic control are mentioned to reduce sound radiated by the structure: the acoustic approach or the vibro-acoustic approach. In both cases integrated actuators in structure materials are necessary to realise feasible products. Furthermore the development of an efficient shaker for Active Isolation techniques is described. The prototype of TNO TPD can produce a force of 400 N up to 250 Hz at a good performance-volume ratio.
To enhance the robustness of the active control applications, the use of the subspace identification based control methods are developed. The robustness property of subspace identification methods forms the basis of an accurate model updating mechanism, using small size data batches. The performed simulations reveal excellent robustness performance under very general noise conditions or during operation of the control system.
Furthermore the development of the techniques can be exploited to realise sound comfort requirements to enhance audible communications of vehicle related applications.
To anticipate to these developments in the automotive industry, TNO has set up a Sound and Vibrations Research Centre with Twente University and a research program on Smart Panels with the Delft University. To investigate the potential markets and applications for sound comfort in the means of transportation, TNO-TPD and the Institute of Sound and Vibration Research in England (ISVR) have agreed on a co-operative venture to develop and realise 'active control of electroacoustics' (ACE).

Keywords: Active noise control, active vibration control, modal sensors , preconditioned actuators, high force density actuators, fast tracking algorithm, subspace identification, state-space model, block Filtered-U LMS, robust algorithms, sound comfort.



Graph 1. Measured result based on this theory using an aluminium sandwich plate of 60 cm x 75 cm and 6mm thickness

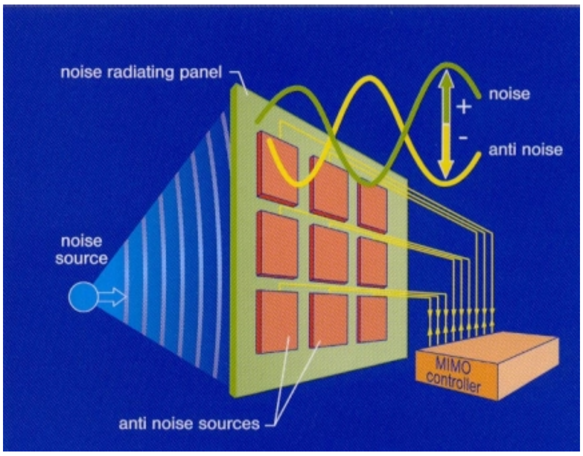


Fig. 1. Neutralisation by anti-sound layer

In the first generation of Active Noise Control (ANC) systems for the interior of cars or aircraft, the (primary) acoustic wave field was controlled with a secondary wave-field which was generated by loudspeakers. It was a straightforward approach but commercially not very successful. The (many) loudspeakers took too much space and weight, the global performance was not always satisfactory and the costs of the system were too high. For that reason, researchers in the field of Active Noise and Vibration Control started to look at other types of ANVC systems with which interior noise could be reduced. At TNO we focussed on two types of systems: Active Structural Acoustic Control (ASAC) systems and Active Isolation Control (AIC) systems. An Active Structural Acoustic Control system reduces sound radiated by the structure (for instance the roof or the firewall of a car), by acting on the structure itself or by generating an acoustic wave field just in front of the radiating wall. In AIC systems, the vibrations due to a source somewhere in the structure (for instance the engine of a car) are isolated before they can reach the radiating wall or panel.

Both types of systems require transducers and a control approach, different from the conventional systems with loudspeakers and microphones. TNO is working on both the transducers and the control approach for ASAC systems as well as AIC systems. In ASAC systems we aim at an integration of actuators, sensors and control unit in the (composite) panel: a thin and lightweight ‘smart’ panel with a high acoustic transmission loss.

ASAC systems

Transducers integrated in the material

An Active Structural Acoustic Control system reduces sound radiated by the structure (for instance the roof or the firewall of a car). Two approaches can be used to reduce sound radiated by walls: the acoustic approach or the vibro-acoustic approach.

In the acoustic approach a thin layer of flat (anti) acoustic actuators is placed just in front of the radiating wall. These actuators can be for instance small, flat loudspeakers or a film of a piezo-electric polymer. The sound radiated by the wall is neutralised by the thin anti-sound layer just in front of the wall (see fig. 1).

In the EC funded project FACTS, extensive research to the ASAC acoustic approach has been carried out. The concept is attractive, but it has not been possible to develop suitable actuators (thin, high displacement, broad frequency range, (Necati, ISME25, 2000).

In the vibro-acoustic approach, actuators are fixed to the wall. The actuators are controlled to modify the vibration pattern in such a way that the wall does not radiate efficiently sound any more. The transducers are made of piezo-electric ceramic material (PZT). In experiments carried by TNO TPD, thin wafers as well as ceramic fibres have been used (see photo 1).

Three TNO divisions (Acoustics, Material Technology, Centre of Lightweight Constructions) and the Faculty of Aeronautic Engineering of the University of Technology Delft are co-operating in an R&D program to the development of smart materials based on piezo-electric ceramic materials integrated in composite materials. The research focuses on the integration of the transducers in (curved) composite materials and the control strategy. The material properties of PZT generally are quite different from the material properties of the composite materials, and so in this phase of the TNO research project to the integration aspects mainly concern the form of PZT (thin plates, strips, fibers), the electrodes and type of glue to be used. So far, a major progress has been made in the control strategy.

Control system

The control system comprises the sensors, actuators and algorithm, where the choice for the algorithm partly depends on the type and configuration of the sensors and actuators. In this section the emphasis is on modal sensors because of the increased robustness of this type of sensor. Structural sensing is assumed due to the impracticality of pressure sensors in far field regions and the importance of a minimum of delay for the performance in a feedback system.

Modal sensors

For the reduction of sound transmitted through a plate we are interested in the vibration patterns of the plate that radiate most efficiently. The concept of radiation modes can be used to determine these vibration patterns if a theoretical description of the acoustic environment is available. It has been shown that the radiation modes are real valued (Borgiotti, JASA, 1990) and therefore, in principle, allow delay-free sensing of acoustic radiation. The practical implementation of these particular radiation modes is complicated by the fact that both the radiation mode shapes as well as the efficiencies are functions of frequency. Assuming fixed radiation mode shapes while using frequency dependent weighting can

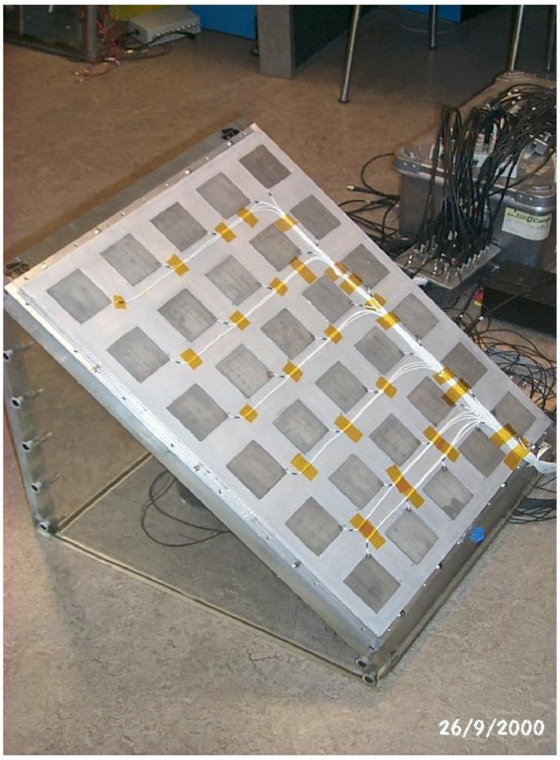


Photo. 1. Experimental set up with ceramic actuators fixed on a composite plate

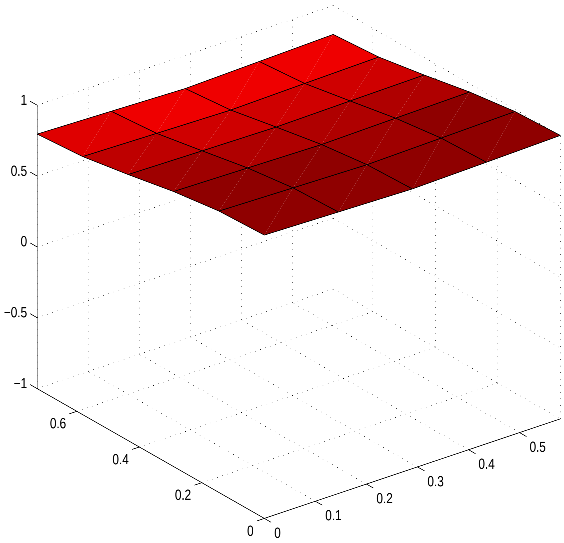


Fig. 2a. Strongest radiation mode in an enclosed space at 145 Hz based on simulation

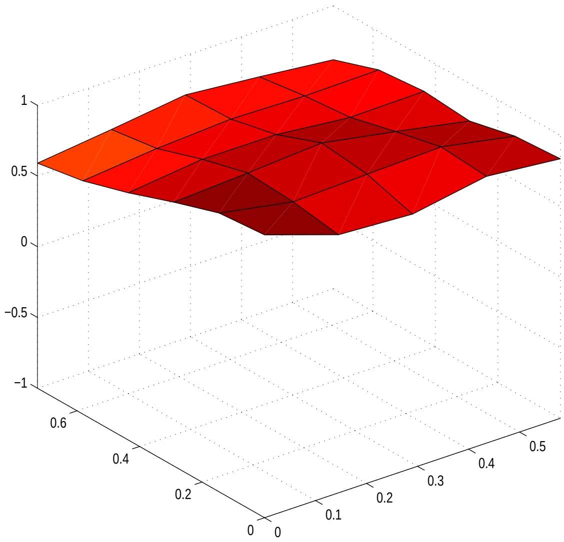


Fig. 2b. Strongest radiation mode in an enclosed space at 145 Hz obtained from measurements

make good approximations.

Various sensor quantities can be used for a radiation modal sensing scheme. In the early papers on the subject the radiation modes were formulated on the basis of the measurement of the velocity of the structure. The use of nearfield pressure sensors in a radiation modal sensing scheme has been described in (Berkhoff, JASA, 2000). A measured result based on this theory using an aluminium sandwich plate of 60 cm x 75 cm and 6mm thickness, 3 piezoelectric actuators, 3 radiation modal error signals obtained from 16 microphones, is shown in graph 1. The primary disturbance signal was broadband noise incident on one side of the panel.

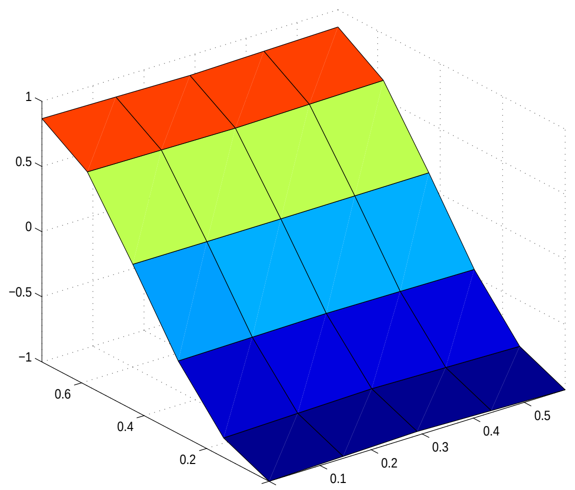


Fig. 3a. Second strongest radiation mode in an enclosed space at 303 Hz based on simulation

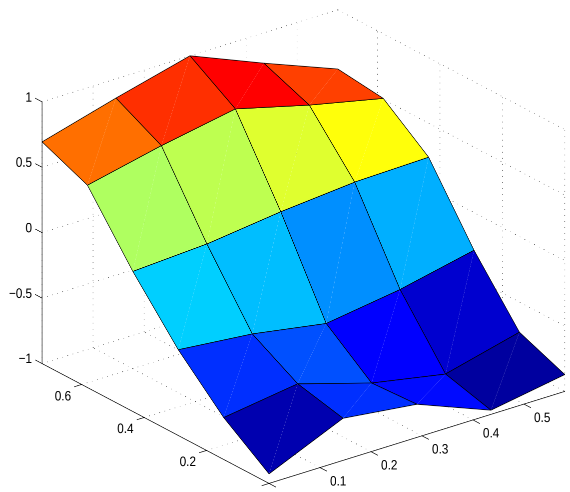


Fig. 3b. Second strongest radiation mode in an enclosed space at 303 Hz obtained from measurements

Also piezoelectric sensors can be used to arrive at radiation modal error signals (Berkhoff, JSV, 2001). An advantage of the use of piezoelectric patch sensors is that the sensors can be made to perform a spatial integration if the spatial extent is sufficiently large. This leads to advantages for the design of the controller because of the inherent rolloff at high frequencies and the corresponding increase of robustness. A disadvantage of the use of piezoelectric patch sensors is that the out of plane movement of the panel at the boundaries can not be sensed.

Measured radiation modes

Previous radiation modal sensing schemes have been based on the assumption that a theoretical description of the radiation characteristics of the panel is available. In many cases this is a questionable assumption. In the methodology approach of TNO, the transducer configuration is based on the measurement of these radiation modes in situ. This allows for improved performance in practical situations. In some cases these measurements can also be used for the calibration of the individual sensors. Methods for the measurement of the radiation modes are described in (Berkhoff, ICSV8, 2001). An example is given of measured radiation modes and corresponding simulated radiation modes in an enclosed space.

In Fig. 2, a comparison is given of the strongest radiation mode at 145 Hz according to simulations (Fig. 2a), and the corresponding measured result (Fig. 2b.). In Fig. 3, a comparison is given of the second strongest radiation mode at 303 Hz according to simulations (Fig. 3a), and the corresponding measured result (Fig. 3b.).

Preconditioned actuators

As for the sensor configuration, the design of the actuator configuration is based on a maximum

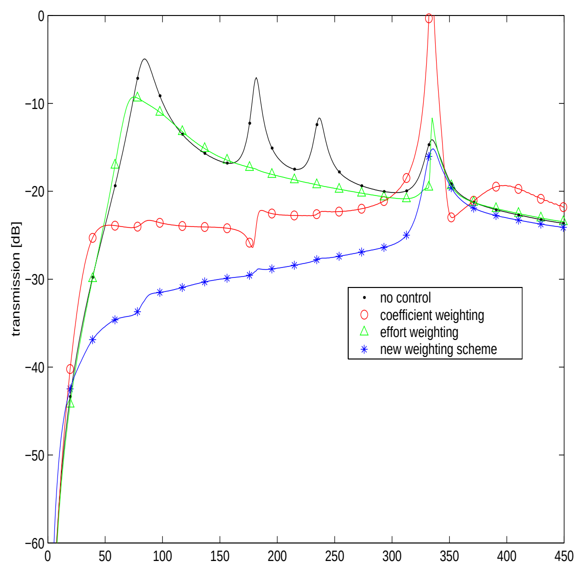


Fig. 4. Sound radiated from a plate without control and with control using three different feedback control strategies.

coupling to the most important acoustic modes in the frequency range of interest, in this case the low frequency range. Another criterion is the amount of energy introduced by the actuator that can not be sensed by the error sensor. This can lead to increases of sound pressure levels at high frequencies if low frequencies are reduced. In order to reduce these undesired contributions at high frequencies a special preconditioned actuator configuration was designed. As compared to previous methods based on effort weighting or coefficient weighting, the new control strategy not only leads to increased reductions at low frequencies, but also to better performance at high frequencies, i.e., virtually no increases of sound power in the uncontrolled frequency ranges. A simulated result is given in Fig. 4.

Active Isolation Control

The actual source causing the vibration, and the corresponding noise radiation of plates and panels, is often a machine, engine, hydraulic system or other mechanism. This means that it can be more efficient to reduce actively the vibrations somewhere in the transmission path, rather than reduce the radiation of the panel. In this way a sub system like for instance the engine of a car can be isolated from the rest of the system.

In AIC the actuator is the most critical element: it should be a compact and efficient actuator with a long working life being able to generate high dynamic forces

Actuators with a high force density

The actuator design from TNO is based on an integrated design of electromagnetic, mechanical and thermal characteristics. Finite Element simulations were performed for the electromagnetic design as well as for the design of the mechanical suspension.

An efficient electromagnetic configuration is used with special emphasis on reduced eddy current losses, leading to an improved frequency response. In addition, the mechanical parts were optimised for minimum fatigue. Another important design aspect is the thermal design. The design was optimised for a minimum temperature even at sustained operation. At nominal force and input power there is still a substantial margin between absolute maximum temperature and the actual maximum temperature.

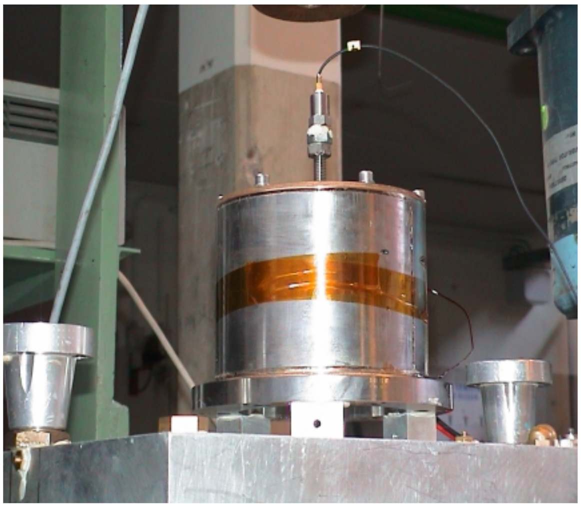


Fig. 5a TNO actuator in test rig

The prototype has a diameter of 16 cm and a height of 16 cm, at a weight of 14 kg. The force is nominally 400 N continuous rms with a roll off of 3dB/octave for frequencies larger than 250 Hz. No active cooling is required even at sustained forces of 400N. Distortion levels are below –35 dB at 400N. A comparison of the new 400 N actuator with a 200 N shaker Derritron VP4, which has 3 times the weight of the new actuator, and which requires active cooling, is given in Fig. 5b.

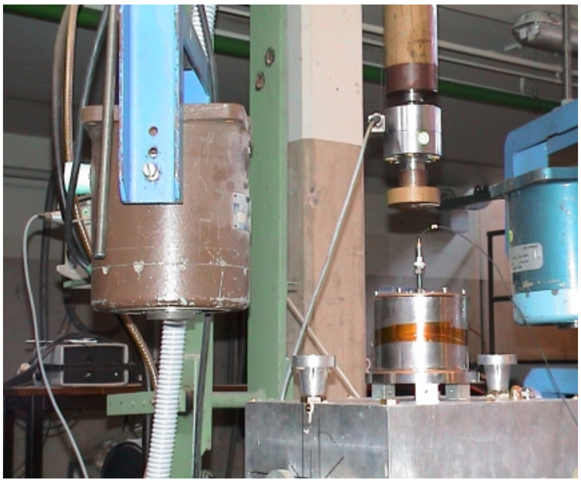


Fig. 5b. 400N TNO actuator in comparison with 200 N Derritron shakers.

Robust adaptive control

The core of the control system is the controller and the control algorithm, which is often taken for granted. However, success or failure of a control system highly depends on the design of the specific control algorithm. To create successful control algorithms, the joint Sound and Vibration Research Centre (SVRC) has defined a research program for the development of robust real-time control systems. The main objective of this program is the design and validation of robust active control algorithms. Special attention is paid to the implementation aspects of industrial real-time active control systems i.e. the realisation criteria for the active controller are taken into account in the design of the robust control algorithms. For instance, the complexity of the control algorithms must be as low as possible. These new algorithms will be denoted as the ‘fourth generation’ robust control algorithms.

One of the starting points in the design of fourth generation algorithms is a proper definition of the controller criterion function (Doelman,AC, 1999).

Fast tracking algorithm

Apart from the controller performance (norm reduction of the error-sensor signals), the controller also has to be robust to perturbations in the mechanical system. It is desirable that the performance of the control system remains within predefined bounds when the properties of the mechanical system change. A method for combining desired performance and robustness of the control system is to extend the controller criterion function with a criterion for the control effort. With the extended criterion function, a robust controller can be designed. However, for controlling fast changing perturbations, not only the robustness is an important issue, but also fast adaptation of the control system is needed e.g. reduction of highly non-stationary broad-band noise in vehicles requires very fast adaptation. Recently, in one of the projects of the SVRC research program, an algorithm for fast adaptation has been developed. Fig. 6 depicts results of simulations on a single reference/single output acoustic duct system excited with broadband noise. The controller is initialised with a zero-state vector. In the graph the learning curves of the new adaptation approach (red line) is plotted against an orthodox approach (green line). The blue line depicts the disturbance signal that needs to be cancelled. Clearly, the convergence rate

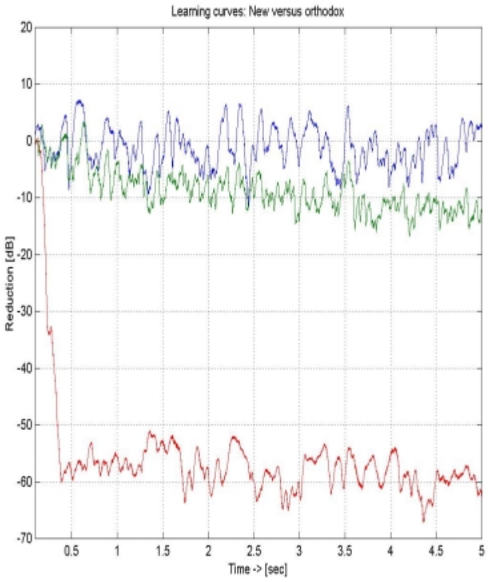


Fig. 6. Convergence ratio of the new versus orthodox algorithm

and tracking capabilities of the new algorithm are superior.

Low order MIMO state space controller
A major drawback of the existing (feedforward) MIMO controllers is the degrading of the performance and of the stability due to long term perturbations in the mechanical -or in the acoustic systems. To cope with these long term changes and to maintain performance and stability, a number of existing update schemes are available (for instance sample-by-sample and block LMS update algorithms). However these update schemes do not implicitly guarantee successful updates and therefore the classical multiple-input/multiple output (MIMO) controllers will in the long run either converge slowly or either become possibly unstable.

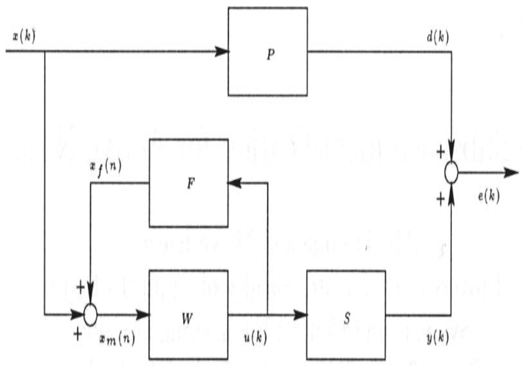


Fig 7. 19th order discrete time realistic acoustical duct benchmark model.

One of the major causes for these phenomena is that classical MIMO controllers are mostly modelled as a FIR controller or as an IIR controller with a large number of coefficients. Identification of the large number of coefficients gives only an accurate estimate of the controller at the higher frequencies in this band at the expense of accuracy at lower frequency.
To address the above mentioned drawbacks the use of recently developed subspace model identification (SMI) methods (Verhaegen, ACSV,1999) for the determination of a low order MIMO state-space controller and its update
based on a block of measurements, is investigated. The (technical) motivation for this investigation is that the subspace identification will give a controller which is accurate in the whole frequency band which is excited, while FIR- or IIR model identification gives only an accurate estimate of the controller at the higher frequencies in this band. A second advantage is the robustness property of the SMI methods, which enables to identify and to update a subspace model accurately under very general noise conditions or during operation of the control system in a non-iterative manner.

As a result of the investigation a robust procedure for tuning IIR controllers for ANC is developed. With the newly developed 'Subspace Identification identify for Active Noise Control' (SIANC) update-procedure, MIMO controllers with excellent performance and robustness has been derived (Fraanje, CDC100, 2000)

Comparison between SIANC an LMS methods
The comparison is illustrated on a 19th order discrete time realistic acoustical duct model. In this model P, S and F are discrete-time SISO IIR models derived by a sampling frequency of 1000 Hz, all have the same denominator polynomial. In the simulation P is only used to generate the disturbance signal $d(k)$. Because the intrinsic feedback is exactly known,

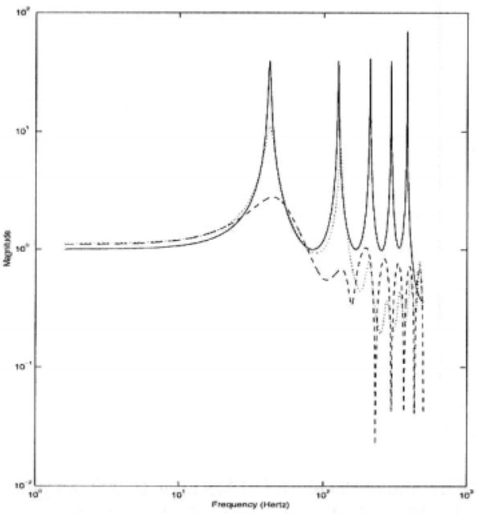


Fig. 8. Frequency response of controller.
Solid = optimal controller
Dashed = Block FuLMS (N=15, 80000 samples)
Dotted = Block FuLMS (N=15, 10000 samples)

the performances of SIANC for the configuration with or without intrinsic acoustic feedback F are the same.
The noise source signal $x(k)$ is band limited white noise with a bandwidth of 200Hz, and causes the disturbance signal $d(k)$. For the block FuLMS method, we choose the controller of order 15, because lower order controllers showed slower convergence. The design results illustrated in fig. 8, where thefrequency response of the optimal feedforward controller is shown (solid), and also the frequency response of the controllers derived by block FuLMS after 10000 samples with order 15 (dotted) and after 80000 samples (dashed).
The controller is also identified and updated using subspace model identification (using the SIANC method). The results are depicted in fig. 9.
Comparing these results, we conclude that the identification and update of the controller gives better performance than the block FuLMS algorithm. Though the identification of the controller is computationally more complex than the update of block FuLMS, only 100 measurements were necessary for an accurate update, whereas for the block FuLMS more than 80000 iterations are needed to obtain significant results.
Comparing the FuLMS and subspace identification results, we conclude that the subspace model identification gives a much better estimate of the optimal controller, which minimises the variance of the error than the FuLMS. This can be explained by the fact that FuLMS identification gives an accurate estimate of the controller at high frequencies at the expense of loss of accuracy at lower frequency (Ljung, 1999)

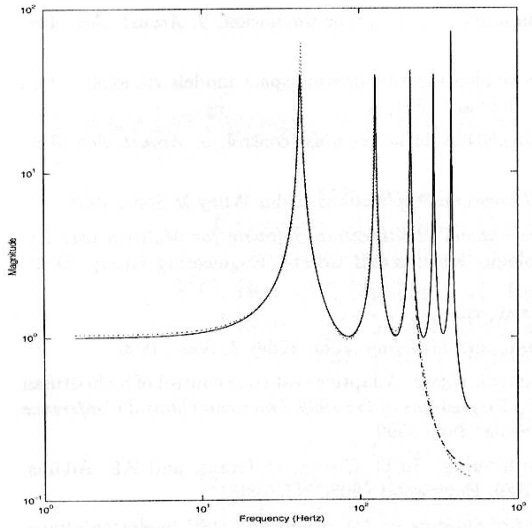


Fig. 9. Frequency response of controller.
Solid = optimal controller
Dashed = 6th state-space controller (100 samples)

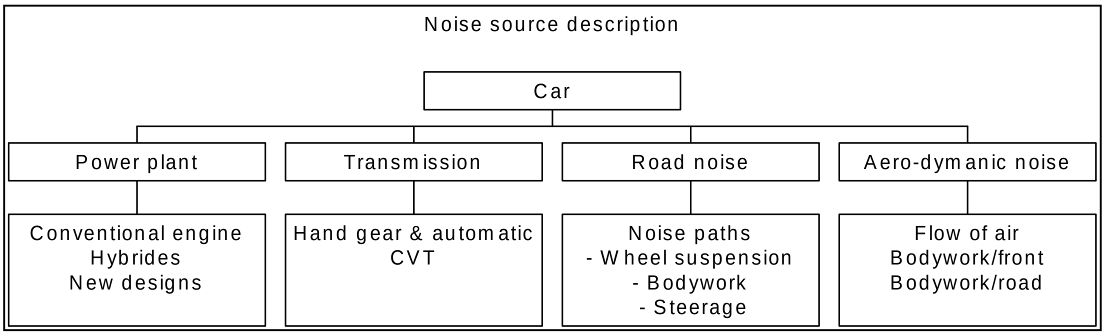
This is confirmed by comparing the results in fig. 8. and fig. 9. which shows the magnitude of the optimal controller (solid), the magnitude of the 6th order controller derived with subspace identification using 100 samples and the 15th order controller derived with block FuLMS identification using 80000 samples. One can see, that the latter is less accurate at low frequency (see the inaccuracy at 42Hz) than at high frequency in the frequency band which is excited (i.e. up to 215Hz).

Noise abatement in future vehicles

The dominant manufacture criteria for the future car could be - the lighter the vehicle, the less fuel will be consumed (competitiveness) and the less pollution will be emitted (EU goals) –. However, lightweight designs are more prone to vibration problems.
To maintain the vibration levels and the overall production of structure-born sound in lightweight vehicles, the isolation capabilities of *sound transmission control* (ASAC) and of *structural dynamics control* (AIC) can be used. This is illustrated with a number of potential noise sources, which are dominant in cars (see the diagram below).

	Vibration	Structure-born sound
Power plant	AIC	ASAC
Transmission	AIC	ASAC
Road noise		
Wheel suspension	AIC	
Steerage	AIC	
Bodywork		ASAC
Aero-dynamic noise		
Bodywork/front		ASAC
Bodywork/road		

(A detailed description of all kinds of noise sources for each sub-system is omitted). For each noise source, a preferred noise control method is selected. The selected methods have the main objective to control the overall structure-born sound in the lightweight car. Besides the control of structure-born sound, the vibration levels at pre-defined comfort points in the car can be controlled. In table 1 the sources, which induce vibration, can be controlled with the *structural dynamics control* (AIC) approach.



Moreover, simultaneously the same approach can be used to control structure-born sound (induced by the same source).
It is obvious that the selection of these methods should be made during the design phase of the car, depending on the noise requirements and comfort requirements

Sound comfort in future vehicles

The research and development of active control systems has in general been intended to complement passive noise abatement techniques in applications in the field of means of transportation. However the potential of recent development, especially the development of dedicated actuators integrated in materials and control algorithms, can further be exploited to other areas of the acoustics, like sound comfort in vehicles and audible communication enhancement in vehicles.

The premises to successful employment of above mentioned application is the control of the acoustic climate in vehicles, which means controlling disturbance noises, enhancing acoustic properties at passenger head position and super imposing virtual acoustics techniques. The most natural and obvious mean to realise the acoustic climate, is the further extension of the controller criterion function as mentioned in previous chapter. Robust noise abatement has been realised with this approach and acoustic properties, like controlling reverberating time in enclosures, can be realised by constraining the controller criterion on performance aspects.

With this technique, the passenger perception of the (standard) passenger car acoustics can vary from a 'dry' anechoically quiet enclosure to a perception of a high-end passenger car acoustics. A quiet enclosure to benefit optimal audible communication with fellow passengers, but not at least with all possible communication equipment. And the latter application can serve merely commercial purposes.

To develop and realise sound comfort applications in vehicles, electroacoustics and ANVC techniques have to merge in the near future, thereby creating 'active control of electroacoustics' as a new application domain.

Conclusions

In the past years, active noise and vibration control has evolved to a technology that can relatively simple be integrated in the existing noise abatement methods. However, the latest development of the technology – control strategies, robust adaptive algorithms, integrated actuators in materials and commercial control systems - creates the possibility to meet noise requirements at the design phase of lightweight cars. Further more the development of the techniques can be exploited to realise sound comfort requirements to enhance audible communications with all kinds of vehicle related equipment.

To anticipate to these developments in the automotive industry, TNO has set up a Sound and Vibrations Research Centre with Twente University and a research program on Smart Panels with the Delft University. To investigate the potential markets and applications for sound comfort in the means of transportation, TNO-TPD and the Institute of Sound and Vibration Research in England (ISVR) have agreed on a co-operative venture to develop and realise 'active control of electroacoustics' (ACE). The aim is to better integrate and co-ordinate their activities on the field ACE with industrial partners.

Appendix

Programmes of the SVRC

TNO and Twente University have set up Sound and Vibrations Research Centre

The Research Centre encompasses three following research programmes:

Robust real-time control systems. This technology can be applied to the fields of active sound and vibration reduction and adaptive optical components.

The integration of active and passive techniques to reduce structure-born sound and vibrations forms the subject of the third programme, “Hybrid isolation of structure-born sound”. It is expected that this research will find applications in shipbuilding, the transport industry and the mechanical engineering sector.

“Computational aero acoustics” uses the results of computational fluid dynamics (CFD) to predict aero- dynamic sound caused by the flow of air around fast means of transport.

The total research programme investment for the years 2000 to 2003 is 8,2 million guldens.

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