Multichannel Active Noise Control Systems and Algorithms for Reduction of Broadband Noise

Authors: ***A.P. Berkhoff[1,1] and J.M. Wesselink[2]***
[1)] TNO Science and Industry, PO Box 155, NL-2600AD Delft, arthur.berkhoff@tno.nl
[2)] University of Twente, Faculty EWI, PO Box 217, NL-7500AE Enschede

Active noise control systems for broadband noise reduction require substantial computing power, especially for multichannel systems and adaptive controllers. Furthermore, speed of convergence can be an issue as well. In this paper, methods and techniques are described that are able to reduce the computational complexity and to improve the speed of convergence. The latter is accomplished by using a control implementation running at multiple sample rates. Decentralised control loops running at high sample rates are efficiently implemented on reconfigurable hardware. For the low to medium sample rates, a full multichannel adaptive control algorithm has been developed that leads to subtantially improved convergence rates at reasonable computational complexity.

Introduction

Research in active structural acoustic control (ASAC)[1], in which structural actuators are used to control sound radiation, suggest that multiple decentralised feedback systems could be useful for noise reduction[2]. Such systems can be based on piezoelectric patch actuators and velocity sensors and a proportional feedback controller. If the actuator is small compared with the structural wavelength and if the velocity sensor is centered on the actuator then the system can be regarded as collocated, having minimum-phase behaviour with phase shift variations not exceeding 180 degrees. With appropriate single-channel feedback, such systems are, in principle, unconditionally stable, even if multiple parallel control systems are used. It can be proven [2] that, for proportional feedback, the function of the control systems is to effectively remove mechanical power from the system; the decentralised control systems therefore add damping to the passive system. Practical implementations could be based on an accelerometer with an additional integrator and a controller with a certain amount of loop-shaping in order to improve performance and/or to improve robustness for non-ideal behaviour. Such systems primarily function as vibration reduction devices. Noise reduction can be a positive side-effect of such systems.

However, with respect to noise reduction performance of such systems, several questions arise. The first question is whether the reduction of noise radiated from such panels is guaranteed under all conditions. Reduction of the vibration of one part of a larger surface that radiates sound at low frequencies does not necessarily lead to a reduction of the radiated noise. Global noise reduction techniques using a centralised processor may be preferable in such cases, such as systems based on the identification of efficiently radiating, diagonalising vibration patterns [3]. Another question is whether the proposed decentralised system provides the most efficient solution for a given noise reduction in terms of actuator effort. Simulation studies by Scholte and D' Andrea [4], for example, show that a significant performance improvement over simple decentralised controllers can be obtained when a distributed controller is used, in which each local controller also receives information from adjacent controllers and adjacent sensors. In the study by Scholte and D' Andrea the performance is expressed in terms of noise reduction and required control effort. Similar conclusions were reported in the work by Tao and Frampton [5]. Another question is whether the system provides the most robust implementation for a given noise reduction.

Slight variations of the configuration also introduce new questions. One such question for example is whether the noise reduction performance is still sufficient if a strain sensor is used instead of a velocity sensor. In such cases an in-plane coupling between the actuator and sensor exists which could disturb the desired sensing of bending motion. Such a disturbance of sensing bending motion by in-plane coupling could reduce the effectiveness of the system for noise reduction applications. Systems with in-plane coupling for which significant noise reduction is desired would likely benefit from distributed control systems.

Another variation of the configuration is such that not the surface vibration level of the controlers itself, or the related noise radation, should be reduced, but that the sound pressure level at a position remote from the panels should be reduced. If the sound pressure at that position is not uniquely determined from the transmission through all considered panels, then reduction of sound transmission does not suffice anymore. In such cases, certain panels should also act as loudspeakers. The latter case is almost allways relevant since, in the majority of applications, either the source can not be completely shielded from the receiver, the transmission paths from the source to the receiver are unknown, or the source is unknown. If the sound pressure at a certain location is to be reduced and if additional reference sensors are unavailable then it would also be beneficial to use acoustic sensors on the panels instead of velocity sensors. The acoustic sensors can be used to reconstruct the sound pressure at the intended position without doing phyisical measurements at that position[6]. Also in such configurations, at least some coupling between the different control units is necessary, such as provided by a distributed controller or a fully centralised controller.

The above examples show that for certain specific systems with specific applications fully decentralised control can be useful. For the majority of applications however, a certain coupling between the different control units is convenient or even necessary. Such coupling issues are important for the decisions regarding cost-effective hardware. In general it can be observed that more centralisation is needed at lower frequencies and that fully decentralised systems often require relatively fast controllers with sufficiently small latency. In the following, a hardware architecture will be presented that enables the implementation of such combined decentralised/ distributed/ centralised systems.

Hardware architectures

Architecture for centralised control and local implementation of distributed/ decentralised control

Figure 1 gives an example of a configuration with a centralised controller connected to a series of distributed/ decentralised control units. The central processor generally operates at lower sample rates than the distributed/ decentralised controllers. The distributed/ decentralised units perform local AD-DA conversion and local interpolation/decimation (Fig. 2). The central controller is able to control and monitor all actuators and sensors, respectively. Standard network protocols such as USB 1 , USB 2, or FireWire were found to be unsuitable for this application because of the large or unpredictable latency. Therefore, a dedicated low-latency protocol was implemented in order to enable feedback control and time-critical feedforward control over the network. Figure 3 shows the realisations of the central controller, the network interface for the central controller and a distributed/ decentralised controller, which, in this case, also contains the power amplifiers and analog sensor preconditioning, as well as interpolation/ decimation, AD-DA conversion, and the network interface.

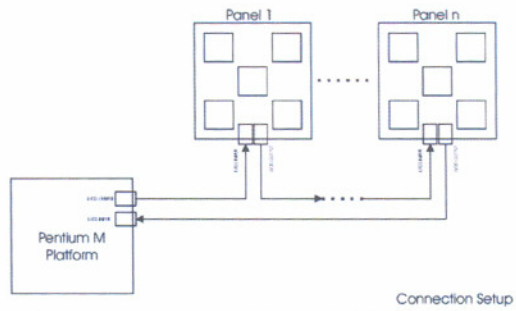

Fig. 1. Central controller and decentralised/ distributed control units connected by a digital high-speed network.

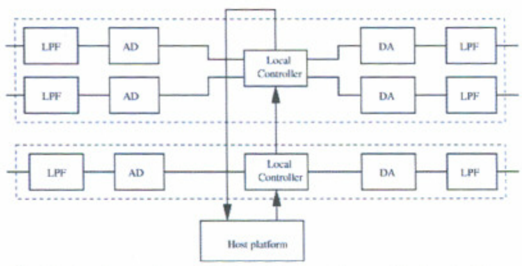

Fig. 2. Configuration of the local controllers with local AD-DA conversion, local interpolation/ decimation filtering and connection with the centralised controller.

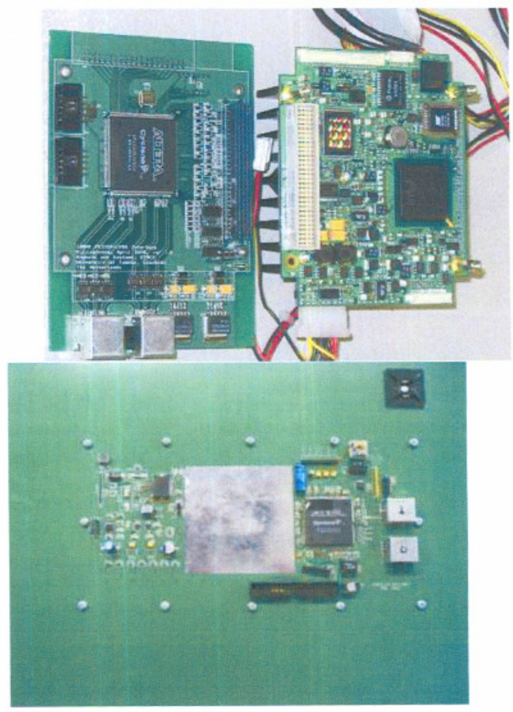

Fig. 3. Central controller and network interface for connection to the decentralised/ distributed controllers (top); decentralised/ distributed controller with integrated power electronics and local control electronics (bottom).

Hardware architecture for centralised control with integrated hardware for decentralised/ distributed control

Figure 4 gives an example of a central CPU controller based on an Intel Mobile architecture. An extension module provides all AD-DA conversion and filtering for 16 input channels and 16 output channels. Filtering is performed digitally on FPGA. The filters are fully programmable, enabling a careful tradeoff between minimum group-delay and maximized stop-band attenuation. The system also supports jitter-free sub-sample delay sample mode, leading to a further reduction of the system latency. A comparison between regular one-sample delay mode, sub-sampe delay mode without jitter-elimination (feedthrough mode), and the jitter-free sub-sample delay mode is provided in Fig. 5. For this system an RT-Linux based operating system is used; the control systems are developed from Simulink, using a real-time implementation with the Matlab RealTime Workshop.

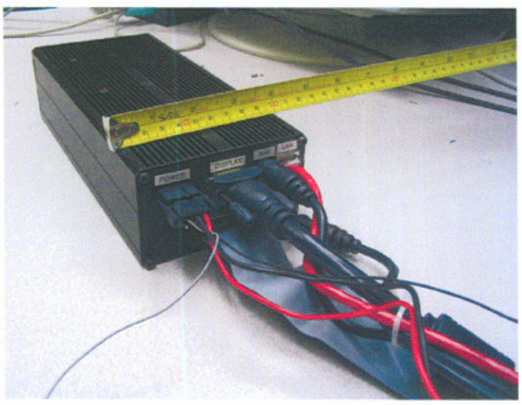

Fig. 4. Centralised controller with integrated 16-channel AD and 16-channel DA conversion, interpolation/ decimation, and possibility for integrated high-speed distributed/ decentralised control.

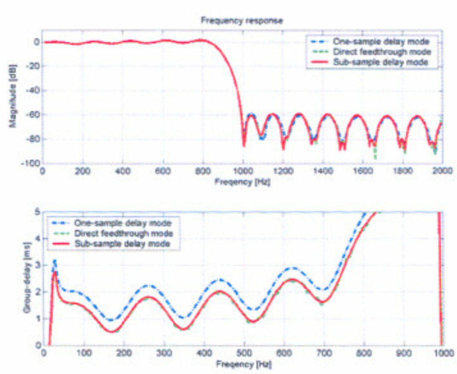

Fig. 5. Control system transfer characteristics. Magnitude and group-delay of minimum-phase interpolation/ decimation filters for three different sampling modes.

Algorithms

Rapidly converging algorithm for multichannel broadband noise reduction

At relatively low frequencies where a strong interaction in the acoustic field exists, a fully coupled Multiple-Input Multiple-Output control algorithm is used. The particular algorithm that has been developed is able to use multiple reference signals in an efficient way. This newly developed algorithm is called regularized modified filtered-error algorithm [7]. The filtered-error algorithm makes a more efficient version of the filtered-reference algorithm if more than a single reference signal is used. The modified version of this algorithm uses preconditioning in combination with a double set of control filters in order to eliminate adverse effects on convergence of phase distortion and delays in the adaptation loop. Such an implementation is made possible by using a state-space based description of relevant transfer functions, for which efficient and robust decomposition techniques exist. Regularization has been implemented in various parts of the algorithm, with the most important being the generalized effort weighting. The algorithm has been implemented successfully in both feedforward and feedback configurations. Fig. 6 shows a block diagram of this algorithm.

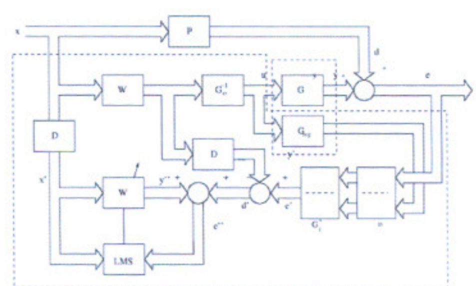

Fig. 6. Regularized modified filtered-error algorithm for adaptive reduction of broadband noise allowing multiple references, multiple error signals and multiple actuators.

An example of the performance of a feedback version of this algorithm will be given for the reduction of noise transmission through a sandwich panel controlled by piezoelectric patch actuators and piezoelectric sensors. The sampling frequency is 2 kHz. The algorithm has been implemented through a Simulink interface for RT-Linux running on the hardware as shown in Fig. 4. The panel was excited with noise from a loudspeaker driven with white noise. The amplitude of the 5 sensor signals as a function of time is given in Fig. 7. It can be seen that the speed of convergence of this adaptive algorithm is quite high.

After fractions of a second already the major part of the noise reduction has been obtained. The remaining noise reduction is obtained after some additional convergence time. Special feedforward versions of this algorithm have also been developed. The basis of the algorithm including its variants have been patented.

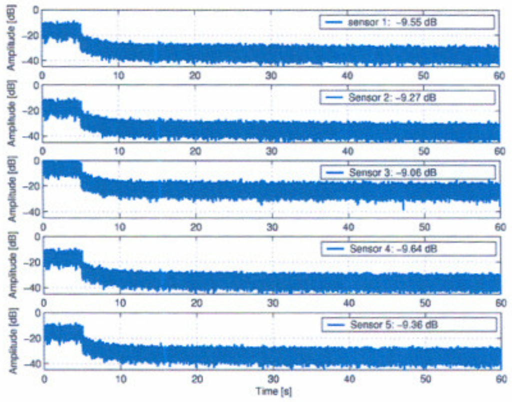

Fig. 7. Amplitude of the 5 sensor signals as a function of time showing the convergence properties of the algorithm of Fig.6.

Conclusions

A hardware architecture for combined centralised/ distributed/ decentralised control configuration has been presented. Two different implementations of such an architecture have been shown, using a controller with a network-based AD/DA system and a controller as a module on a combined AD/DA system. Both architectures allow decentralized control loops operating at very high frequencies. For the lower frequencies, where fully coupled control is required, an efficient version of a multiple-reference adaptive algorithm has been presented. This algorithm provides rapid convergence for systems requiring mutiple-channel active noise reduction, also for broadband noise.

Acknowledgements

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