Design of Active Electro-Acoustical Systems

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Introduction

Digital signal processing opens new ways for realizing active electro-acoustical systems required not only in consumer audio equipment (home, car, mobile, ..) but also in professional sound installations and industrial applications such as active noise control. This paper gives an overview on the new possibilities, chances and challenges but addresses also implicit requirements and potential limitations.

Electro-acoustical engineering progresses relatively slowly but steadily. We still find an electro-dynamical transducer using a voice coil and a magnet, a mechanical suspension made of fabric and rubber, paper cones, horns and even the array lines are not completely new. Most of the innovations made in the last years are not visible for the consumer because they are hidden in the material, in details of the design and way of manufacturing and are implemented in the electrical control system. It is more an evolutionary process where new ideas and inventions are evaluated pragmatically considering practical aspects like robustness, easiness of manufacturing and use but also cost, weight and the subjective listening impression. Another reason for the "highly-damped" progress line found in electro-acoustics is the complexity of the issues and the inter-disciplinary work required between classical acoustics, mechanics, power electronics, signal processing and psycho-acoustics.

Before the paper discusses the new possibilities of DSP it is necessary to summaries the particularities of electro-acoustical systems:

- Wave propagation requires a model with distributed parameters.
- The number of actuators and sensors is much smaller than the number of state variables in the mechanical and acoustical system. Due to practical concerns it is difficult to observe all state variables and to control them by an electrical system.
- Some electro-acoustical systems are non-minimal phase and there might be a significant time delay between the electrical outputs and inputs (see Figure 1).
- Due to the low efficiency in electro-acoustical conversion high electrical input power is required to produce significant amplitude in the sound field. Most loudspeaker and actuators behave nonlinear at high amplitudes.
- Most of the electro-acoustical systems are time-variant. The position of actuators and sensors and the boundary condition in the sound field may change. Air temperature and humidity effect the speed of sound. Most loudspeaker materials like fabric, paper and rubber will age over time.
- Most electro-acoustical applications lead to a mass product which should be produced at low cost.

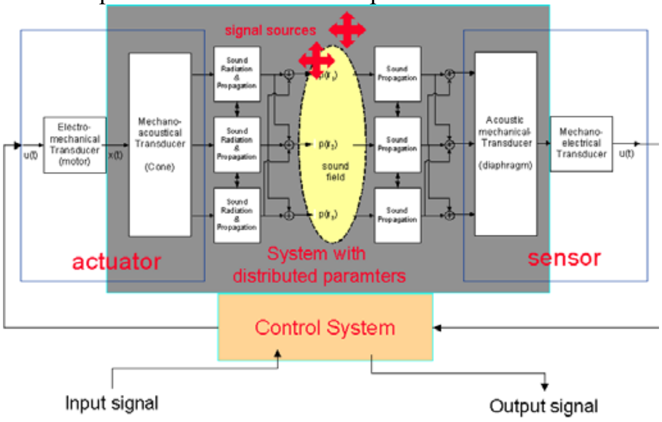

Figure 1: Block diagram of an active electro-acoustical system

New Possibilities of DSP

Digital signal processing allows a direct replacement of the analogue technique by reducing size, weight and cost. For example an IIR filter can be realized most effectively in biquad-structure using 5 – 10 processing cycles only. This makes it possible to realize more complex electrical systems. More important are the new features:

- The properties of the digital transfer system are clearly defined by numerical parameters which can be varied, replaced, stored and recalculated.
- Time signals such as state variables measured in the acoustical system can be easily stored in a memory to realize additional delays, FIR and other filter structures.
- Time signals can be multiplied at high precision within one single processing cycle which makes nonlinear signal processing feasible.
- Sophisticated background calculation can be performed to realize adaptive filtering, system identification and other self-learning capabilities.

The new degrees of freedom require a new methodological approach how to define the targets, to analyze and model the electro-acoustical problem and finally to develop the optimal solution comprising hardware and software components.

1st Step: Definition of Target Performance

The development of new audio equipment and other electroacoustical equipment should start from consumer perspective and the requirements of target applications. This is not trivial because we need a better understanding of the objective and subjective factors contributing to the perceived sound quality. For example it is not a good idea to equalize perfectly the amplitude and phase-response of a loudspeaker in one direction in an anechoic environment or at the one single point in real room while impairing the overall sound quality at other points of interest.

More mathematically speaking the definition of the target may require a cost function which should become minimal in the particular solution. This optimization is not only crucial for product development but might be also the basis for realizing a product with self-learning capabilities which may adapt automatically in the final application (and compensates for the diffuse field in a living room for example).
Other practical constraints such as number of actuators, sensors have to be considered already in the 1st Step.

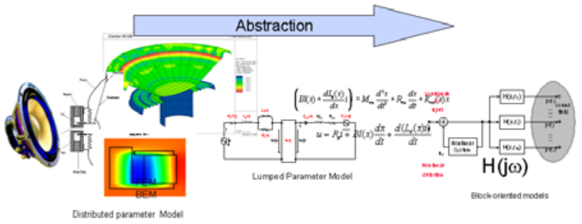

Figure 2: An adequate model of the electro-acoustical problem is the basis for developing optimal signal processing.

2nd Step: Physical Modeling

Modeling is always a result of an abstraction process where only information which is relevant for the problem is preserved. Not the most accurate model is the best because more complex models containing a larger number of free parameters make system identification more difficult. The cost function defined in the 1st step can be an objective criterion for finding an optimal model. Figure 2 illustrates the variety of models which may relevant in electroacoustics (lumped parameter model, models with distributed models, block oriented models using linear and nonlinear subsystems, …). Special models considering the particularities of the electro-acoustical problem are usually superior on generic models. For example modelling loudspeaker nonlinearities by polynomial filters result in a large number of model parameters and states which are not related with physical parameters (e.g. moving mass) and state variables (e.g. displacement) in a lumped parameter model.

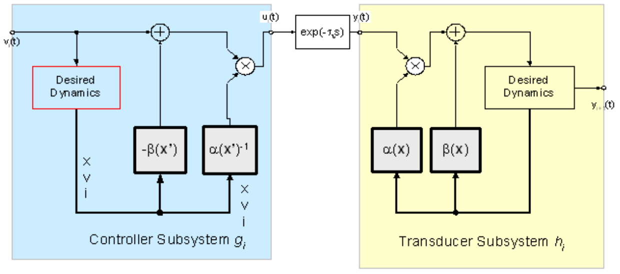

Figure 3: Linearization of loudspeaker systems by nonlinear control (mirror filter).

3rd Step Design of Electrical Control Structure

There are many examples in electro-acoustics where the results of the physical modelling are the basis for finding a dedicated control structure. For example loudspeaker linearization by using the mirror filter in Figure 3 exploits the physics of nonlinear loudspeaker modelling with lumped parameters. The nonlinear distortion generated in the feedback loop in the loudspeaker model (differential equation) can completely be compensated by distortion synthesized in a feed-forward branch in the controller. There are other examples in active noise control (e.g. feedback compensation of a upstream sound in a ventilation channel) or echo cancellation in a hands-free telephone set which use available a priory knowledge from physical modelling.

4th Step: Estimation of optimal Control Parameters

The free parameters of the electrical control structure (FIR, lattice, wave filter) have to be adjusted to the particular application. Again the cost function defined in the 1st step may be criterion for finding the optimal parameter estimates. While the control structure is usually fixed the particular parameters can be used to compensate for variations of the properties of parts used in the electro-acoustical system (e.g. actuators and sensors) or different acoustical or mechanical conditions.

The digital signal processor implemented in the product may directly be used to measure the control parameters. In an off-line scenario an artificial test stimulus may be generated and supplied via the actuators to the mechanical and acoustical system and some relevant state variables are measured by sensors. To compensate for varying ambient condition, aging an adaptive solution is required which should be operative under normal working conditions (e.g. reproducing music).

Self-learning or adaptive solutions need a monitoring of the output signal or other state variables in the electro-acoustical systems. For practical reasons it is desirable to use available sensors (microphone in a hands-free telephone system) or the actuator itself as sensor (loudspeaker linearization based on current measurement).

5th Step: Failure Diagnosis, Protection

Self-learning and adaptive solutions open new ways for performing an on-line diagnostic of critical components used in the electro-acoustical systems especially power amplifiers, sensors and actuators. If the control structure is derived from physical modelling some of the control states may be interpreted as input power, distortion, temperature and other characteristics which indicate an overload situation or a critical aging of some components. Under those conditions some control activities may be stalled and a message may be generated to the user.

Reference

[1] W. Klippel, “Optimal Design of Loudspeakers with Nonlinear Control,” presented at the AES 32nd International Conference, Hillerod, Denmark, 2007 September 21 -23