Multi-Exciter Panel Compensation for Wave Field Synthesis

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Introduction

New multi-channel audio reproduction techniques alleviate the sweet-spot problem at the price of an ever-increasing number of loudspeakers. This development calls for new multi-channel transducer systems. The problems and solutions with the use of multi-exciter panels for wave field synthesis are discussed in this contribution.

The theory of wave field synthesis (WFS) has been initially developed at the Technical University of Delft over the past decade [1]. In contrast to other multi-channel approaches, it is based on fundamental acoustic principles. The foundation of WFS is given by the principle of Huygens and its mathematical formulation by the Kirchhoff-Helmholtz integral. The latter states that the acoustic wave field inside a bounded area can be controlled by surrounding this area with loudspeakers leveled with the listeners ears. WFS is capable of reproducing the sound of virtual sources outside and inside the listening area.

The fact that loudspeakers can only be mounted at discrete positions results in spatial aliasing due to spatial sampling. Fortunately, the human auditory system seems not to be very sensitive to these aliasing artifacts when the loudspeaker distance remains within specified limits. It has been shown that a loudspeaker distance of $\Delta x = 10 \ldots 30$ cm is suitable in practice.

A WFS system requires a relatively high number of loudspeakers due to the dense loudspeaker spacing. The loudspeakers themself should cover the entire frequency range of typical audio systems and at the same time have rather small dimensions. On the other hand, they should be simple to build to keep the costs of a WFS system bearable and unobtrusive to allow seamless integration into the listening room. The next section will introduce the concept of multi-exciter panels as potential solution.

Multi-Exciter Panels

Multi-Exciter panels (MEPs) are a relatively new type of multichannel loudspeakers that have been developed in the course of the European project CARROUSO [2]. MEPs have a relatively simple mechanical construction. They consist of a foam board with both sides covered by a thin plastic layer. Multiple electro-mechanical exciters are glued equidistant in a line on the back side of the board. The board is fixed on the sides and placed in a damped housing. The benefits of MEPs are their simple construction and the possibility of seamless integration into walls. Due to their multiple exciters MEPs are designed for the use with WFS. However, because of their simple mechanical construction it can be expected that their characteristics are not comparable to high-quality loudspeakers.

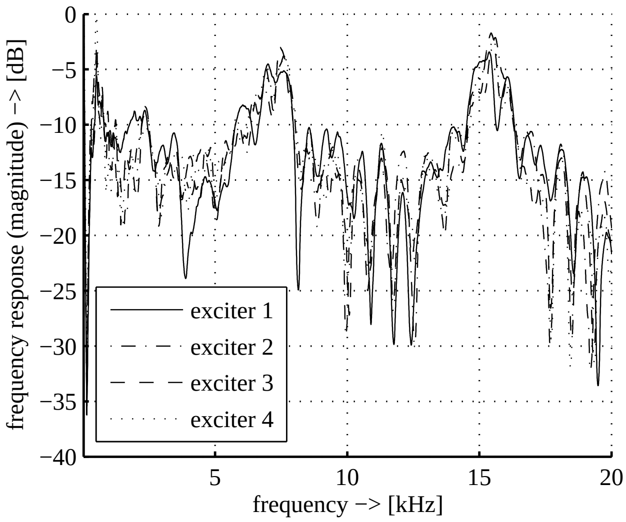

Figure 1: On axis frequency responses (magnitude) of four exciters of the first MEP.

We built four MEPs with eight exciters each. The dimensions of the panels are $1.38 \times 0.75 \times 0.10$ m(W×H×D), the spacing in between the exciters $\Delta x = 17.1$ cm. The next section will discuss the properties of the panels derived from acoustic measurements.

Characterization of Multi-Exciter Panels

We measured the impulse responses (IRs) from individual exciters to multiple microphone positions in an anechoic chamber. First each panel was measured individually. For this purpose the microphone positions where chosen on a parallel axis to the panel with a distance of $d_1 = 1.20$ m. In total 16 microphone positions with a spacing of $\Delta x = 8.55$ cm where measured. The entire measurement procedure for one panel resulted in 8×16 IRs. In a second step the panels where set-up in the configuration when used as WFS system. Two panels where placed side-by-side, the two other where placed at their sides with an tilt angle of 60°. The panels formed approximately the shape of a wide "U". Again the IRs from individual exciters to multiple microphone positions where measured. In this case 32 microphone positions in a distance of $d_2 = 2.54$ m to the center elements of the loudspeaker array. This procedure resulted in 32×32 IRs.

Figure 1 shows the magnitude of the measured on-axis frequency responses of the first four exciter positions (from the left) of the first panel. As can be seen the fre-

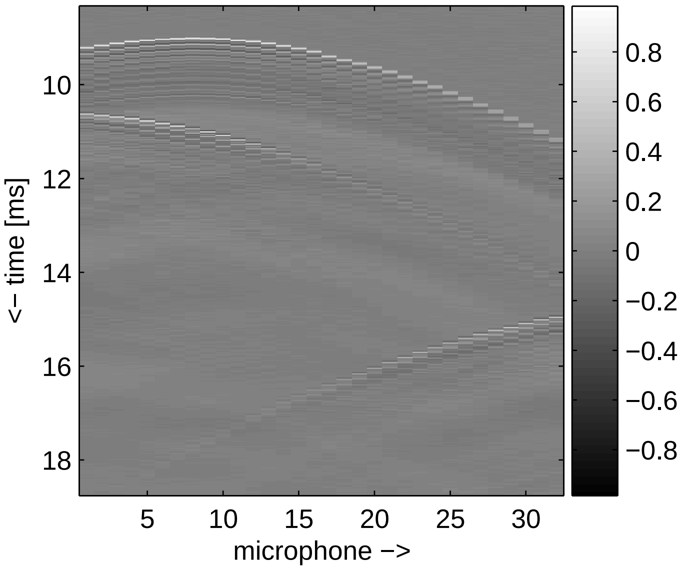

Figure 2: Impulse responses from the 12th exciter to all microphone positions (U-shaped setup).

quency responses do not only differ significantly from the ideal flat frequency response, they also show dependency on the position of the exciter. The position dependency is a consequence of the different distances of the exciters with respect to the support. The remaining four exciters (not shown) have similar frequency responses due to the symmetry of the panel.

Figure 2 shows the IRs from the 12th exciter in the U-setup to all 32 microphone positions. As desired, the shape of the first wavefront visible resembles the shape of a point source. However, there are also traces visible which originate from reflections at the side panels. The trace beginning at $t \approx 11$ ms is caused by the first panel, the trace beginning at $t \approx 15$ ms is caused by the fourth panel. Both panels are tilted with respect to the two center panels. Thus, even in this "open" setup an considerable amount of inter-panel reflections is present.

Compensation of Multi-Exciter Panels

The characteristics of MEPs as presented in the previous section indicate that these cannot be used for high-quality reproduction of sound, unless proper digital pre-equalization is applied. The theory of WFS states that it is sufficient to equalize the MEP responses on a line between the listener and the panel. The wave field in front of that line will then be equalized for all listener positions. However, this is only valid below the spatial aliasing frequency which is given by the exciter distance. The methods used for the equalization of the MEPs can be classified into three classes: (1) individual equalization of each exciter, (2) multichannel equalization, (3) multichannel minimum-phase equalization.

Individual equalization of each exciter can only cope with the frequency response, not with the radiation characteristics. We will not consider this approach further. The IRs from each exciter to each microphone can be regarded as multiple-input/multiple-output (MIMO) system. A joint equalization of all channels of the MIMO system compensates for the frequency and directional response of each individual channel. The multiple-input/output inverse-filtering theorem (MINT) [3] states that suitable equalization filters can be found in nearly all practical situations. However, the calculation can become unfeasible for a high number of channels. Using minimum-phase IRs derived from the measured ones can minimize this problem to some extend. However, the calculation of minimum-phase responses often maintains only the magnitude of the frequency response. As a result, multichannel minimum-phase equalization [4] cannot cope with inter-panel reflections. A promising solution to overcome the complexity issue is to apply the concept of wave domain adaptive filtering (WDAF) for loudspeaker equalization [5]. Unfortunately, listener position independent equalization can only be performed below the spatial aliasing frequency. Above individual equalization of the exciters may be used [4].

Conclusion

We presented the concept of MEP loudspeakers. It has been shown that they are especially useful in the context of WFS. However, their relatively simple construction results in poor reproduction quality. Pre-equalization is therefore mandatory when using MEPs. Different approaches for the calculation of suitable filters where reviewed. The most promising ones are multichannel equalization approaches and wave domain adaptive filtering. Informal listening tests using the algorithm presented in [4] proved that MEPs can be used for high-quality auralization with WFS.

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References

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