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DISTRIBUTED MODE LOUDSPEAKER ARRAYS

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ABSTRACT

The usefulness of Distributed Mode Loudspeakers (DMLs) in arrays has been investigated. The design goal is an array that evenly distributes energy over a hemi-disc. A model has been developed to predict trends of DML array radiation and compared with measurements. This model enables the performance of established array technologies to be tested. When several DML panels are positioned in an array, spatial aliasing results, as would be expected. Conventional array techniques, such as number theory modulation, can improve the radiation characteristics. Complete omni directionality is not achieved.

INTRODUCTION

Transducers are used in arrays for a wide variety of purposes. In reproduced sound, loudspeaker arrays are used because they allow some control over the directivity and frequency response of the radiated sound. The simplest example is probably the column loudspeaker, which achieves a more directional sound at mid-frequencies and so can be used to direct sound towards specific audience areas. Current state-of-the-art approaches use optimisation with digital filters which act on the loudspeaker signals. This gains further control over directivity and is especially useful in forming highly directional arrays for speech reinforcement and public address systems[1]. However, even with filtering of the loudspeaker signals, the performance of the array can be limited by the response of the individual transducer elements. It is very difficult to form a directional array from very omnidirectional elements. Consequently, gaining low frequency directionality from an array of conventional pistonic loudspeakers is difficult. Conversely, it is difficult to form an omni-directional array response if the individual transducers are highly directional, as happens with pistonic sources at high frequency.

This paper concerns the formation of omnidirectional array responses. Instead of using conventional pistonic radiators, Distributed Mode Loudspeakers (DMLs) are used as array elements. DML loudspeakers have a relatively omnidirectional response, and would consequently seem to be a good choice as array elements where an omnidirectional response is required. In this paper, the effects of applying standard array technology, such as Bessel and Barker sequence modulation, are considered.

THEORY

DML Radiation model

The surface velocity of DML vibration is modeled using classical techniques developed by Warburton[2]. Warburton solves a fourth-order equation to obtain the transverse velocity w of the plate. This is done for simply supported, free and clamped boundary conditions. The solution is in the form of the sum of an infinite series of plate modes.

$$w(x,z) = j\omega F \sum_{n=1}^{\infty} \frac{\phi_n(x,z)\phi_n(x_0,z_0)}{\Lambda_n\left[\omega_n^2(1+j\eta)-\omega^2\right]} \quad (1)$$

Here, ω is the angular frequency, F is the force input; (x_0,z_0) the source position, (x,z) the position on the plate where the velocity is required; Λ_n the normalization factor; ω_n the modal frequency; ϕ_n the shape function, and η the loss factor. The shape functions will be simple sine functions when the boundaries are simply supported. When the boundaries are clamped or free, the shape functions assume a more complicated form with a combination of sine, cosine, sinh and cosh terms.

In order to implement the model, a number of physical constants describing the material from which a panel is constructed must be known. These include Young's Modulus E, thickness h, Poisson's ratio ν, mass per unit area M and loss factor η These factors are gained by empirically fitting vibration measurements to the prediction model[3].

Once the surface vibration has been obtained, the resulting radiated pressure must be propagated to a receiver point in space. The propagation can be done using the Helmholtz-Kirchhoff integral equation[4]. If the surface is assumed to be planar and thin, the propagation is governed by:

$$\phi(P) = \iint_F \{\phi(q_1) - \phi(q_2)\} \frac{\partial G(P,q)}{\partial n_q} - \frac{2\partial\phi(q_1)}{\partial n_q} G(P,q)\, dS_q \tag{2}$$

Here the nomenclature set out in reference 4 is followed. ϕ equates to pressure; $\partial\phi/\partial n$ relates to velocity; G is the Green's function; P the location of the receiver; n the panel normal, and q a point on the DML surface. To evaluate this integral the surface pressures must be found. This can be done by using a Boundary Element Method (BEM) solution. Alternatively, if the vibrating surface is assumed to be mounted in an infinite baffle, then the differential in the Green's function vanishes and a simple surface integration results.

The prediction model is a simplification of a physical DML panel as measured. The boundary conditions of DML panels are ill-defined as they are typically secured by adhesive foam pads. The panel materials are often anisotropic, yet Equation (1) is defined for an isotropic plate. Consequently, the prediction model will never exactly match measured DML behavior, but this paper aims to use trends in the modelled data to predict significant features in the use of array technology.

Array technology

A typical set of loudspeakers, all radiating in phase, will be affected by grating lobes somewhere in the audio frequency range. The grating lobes are a periodicity effect, often referred to as spatial aliasing. Consequently, to achieve an omni-directional response from an array of transducers it is necessary to process the signals fed to the loudspeakers. There are several established techniques for doing this[5,6] as outlined below.

By applying a modulation sequence with good aperiodic autocorrelation properties, it is possible to reduce periodicity effects from the array. If the sequence has a perfect autocorrelation function, then the response of a modulated array of point sources will be omnidirectional. For transducers with a specific elemental directivity, the modulated sequence enables the complete array to radiate with a directivity equivalent to one transducer acting alone. For example the N=5 Barker sequence is 1 1 1 –1 1, so the array has the fourth loudspeaker signal inverted. This sequence has the best aperiodic autocorrelation properties for a bidirectional, length 5 signal. Other sequences exist, or can be found by a computer search[7]. Some of these require the phase to vary in a more complicated manner than the Barker array, having different phases for all the loudspeakers.

The Bessel array is another modulation scheme, but the design is not based on autocorrelation principles. A simplified version of Equation (2) gives the radiation from a series of sources as:

$$\phi(P) = \phi_1(P)\sum_{1}^{n} a_n e^{jkx\sin(\theta)} \tag{3}$$

Where ϕ_l is the radiation from one source alone, θ the angle between the array normal and the receiver, k the wavenumber, x a vector along the array and a_n the modulating sequence. This is a simplification of Equation (2) and is only valid in the far field and if there is no mutual interaction between the panels. Bessel functions have the following property[5]:

$$\left| \sum_{n=-\infty}^{\infty} J_n(z) e^{j\beta} \right| = const. \tag{4}$$

Where β and z are constants. So if the modulation sequence, a_n are chosen appropriately from Bessel function, the sum in Equation (3) will be constant, and so the radiation from the array will be the same as from a single transducer. The only problem is that an infinite number of elements cannot be used and so truncation effects can be important.

Although Bessel arrays are designed based on Equation (4), they also tend to have good autocorrelation properties. Figure 1 shows the autocorrelation function for a linear, Barker and Bessel arrays. The Bessel array has lower side lobes, and therefore would be expected to be a better modulation sequence.

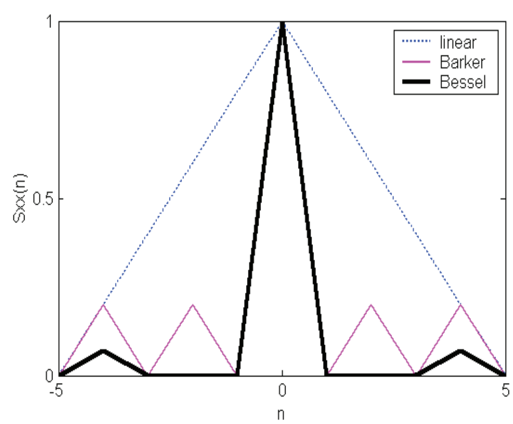

Figure 1. Autocorrelation function S_{xx} for three N=5 sequences.

Barker arrays use simple phase inversion. Bessel arrays usually use a combination of phase inversion and magnitude changes. For ideal point sources, a Bessel array will have better directivity than a Barker array, but the Barker array is more efficient because all elements radiate the same energy unlike a Bessel array where some elements are attenuated[5].

MEASUREMENTS

The polar response of a DML array was measured in an anechoic chamber. The DML array was mounted in a baffle to allow direct comparison with a simple radiation model. The arrays tested were a linear array and a Barker array based on $N=5$. Figure 2 shows the scattering from the linear array comparing prediction and measurement. Similar results were achieved for the Barker array.

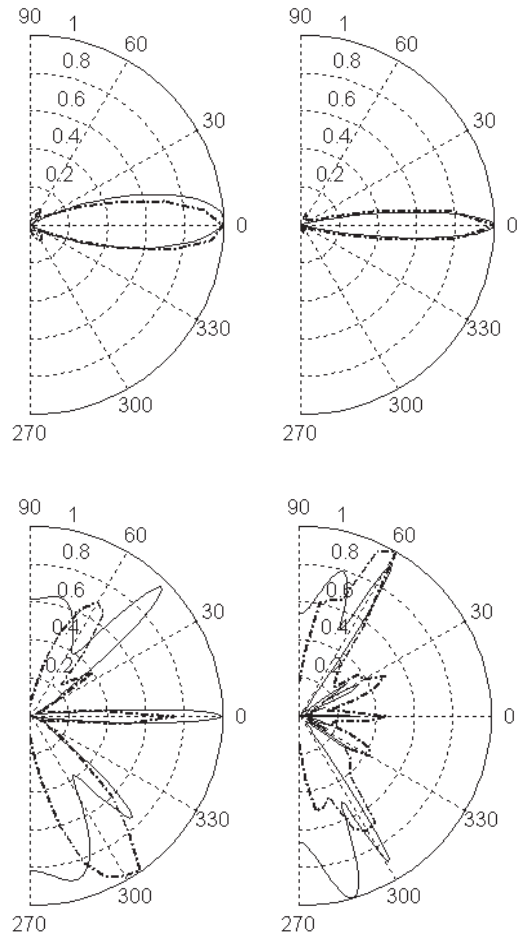

Figure 2. Predicted (solid line) and measured (dashed line); Radiation from a linear array of 5 DMLs each approximately A4 in size. Octave band results, top left 500Hz, top right 1kHz, bottom left 2 kHz, bottom right 4 kHz. Results are shown as mean square pressure, with the maximum normalised to one.

As might be expected an exact match between theory and prediction was not achieved. There are many variables in the plate vibration model which are not precisely known: the panel material is to some extent anisotropic, the exciter does not act at a point (and actually exerts a force over a vibrating ring), the boundary conditions of the panel are ill-defined etc. The aim of the model was not to achieve an exact match, but to derive a numerical model which correctly predicts trends in the panel behavior. The predicted and measured polar responses are expected to vary in frequency in a similar manner, in order to allow an analysis of generalized DML array behavior to continue using prediction models. This expectation has been borne out in measurement.

SIMULATIONS

A variety of array modulation types were explored using the prediction model. Below the results for the Barker and Bessel arrays are reported. Figure 3 compares the linear array, a single DML panel and a Bessel array of DML panels at 2 kHz. Figure 4 is similar except the modulated array used is a Barker array.

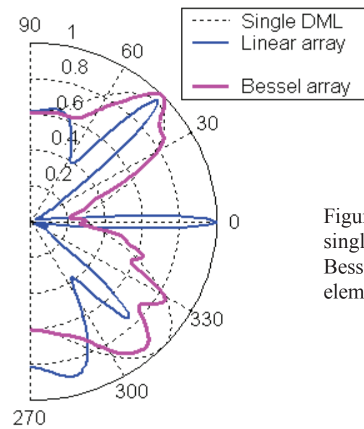

Figure 3. Comparison of a single DML with Linear and Bessel DML arrays - 5 elements. 2kHz octave band.

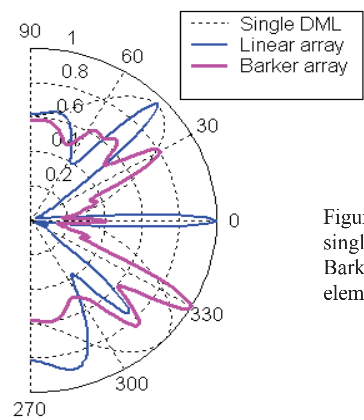

Figure 4. Comparison of a single DML with Linear and Barker DML arrays - 5 elements. 2kHz octave band.

Both the Bessel and Barker arrays cause the radiated polar responses to more closely resemble the single DML. The zero order lobe at zero degrees seen in the Linear array is greatly suppressed and the grating lobes at ±45° are broadened. In general, the Bessel array performs better than the Barker array in recovering the single panel response. A similar result is found for pistonic and point sources where the Bessel array also outperforms the Barker array. This is to be expected given the better autocorrelation properties of the Bessel array.

It is suggested that the Bessel array fails to completely recover the single panel response because of truncation effects in the formation of the Bessel array coefficients. The side-lobe energy in Figure 1 is low, but is not completely zero. This results in ripple in the polar array directivity. Despite this, the Bessel and Barker sequences are shown to give significant improvement over the Linear array, and similar results were obtained for all octave bands from 500 Hz to 4000 Hz.
It is suggested that the reason the Barker array performs less well is that side lobes in the sequence autocorrelation are significantly larger than for the Bessel case. Figures 5 and 6 show Barker-modulated array directivity using pistonic and point-source elements. Again the modulation in Figure 4 lie with the use of Barker modulation rather makes the polar response more similar (but not identical) to that obtained for a single device. This adds weight to the supposition that problems than with the use of DML array elements.

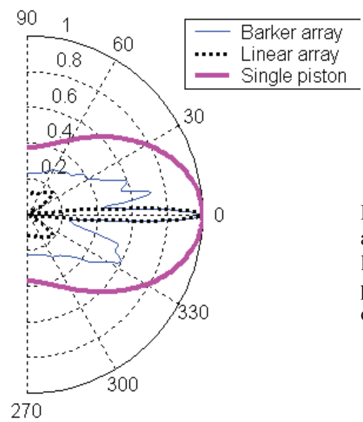

Figure 5. Comparison of a single pistonic loudspeaker and two pistonic arrays. 2kHz octave band.

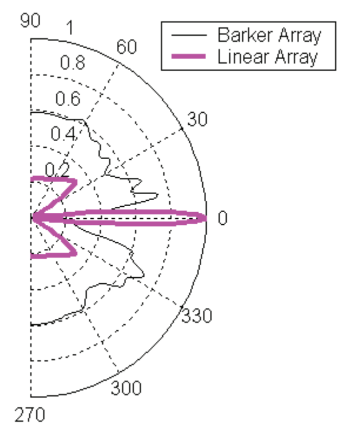

Figure 6. Comparison of two point source arrays. 2kHz octave band.

Although both modulation sequences move the radiated response closer to the polar response of a single panel, the result is not omnidirectional because the individual panels do not themselves exhibit omnidirectional directivity. Measurements on a Barker array show similar results to the predictions.

DISCUSSIONS AND CONCLUSIONS

The application of modulation sequences to DML arrays makes the polar response closer to that for a single DML, but a single panel polar response is not completely recovered. Furthermore, the array response is not omnidirectional because the individual DML elements themselves are not completely omnidirectional.

Data in Figures 2 to 6 are presented in terms of mean square pressure in order to clearly define the limitations of, and differences between, each technique. When pressures are visualised using a more subjectively indicative decibel scale, the performance benefit of the directivity-broadening techniques is more dramatically revealed.
By using DML array elements, the directivity of the array is more constant and broad over a wide frequency bandwidth than would be obtained with pistonic sources. The response in the low-frequency sparse modal region is, however, far from omnidirectional. With this in mind, further work will focus on attempts to use numerical optimisation to improve the directional characteristics of DML arrays across a broad frequency bandwidth which includes the lowest two octaves of sound pressure radiated by the constituent elements.

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