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SPATIAL BANDWIDTH OF DIFFUSE RADIATION IN DISTRIBUTED-MODE LOUDSPEAKERS

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ABSTRACT

The degree to which radiation from a loudspeaker is diffuse may be quantified by a spatial correlation function normalised to the on-axis response. This is true for any loudspeaker type, including the distributed-mode loudspeaker (DML). However, because of the variation in material damping and design-related constraints, correlation commonly varies both with frequency and direction. A modified function, the offset spatial bandwidth of correlation function, is introduced as a means of describing diffuse performance and quantifying its variation over the radiation field.

1. INTRODUCTION

An objective method for characterising the degree to which the acoustic radiation from a loudspeaker is diffuse was first suggested by the authors in [1], with subsequent expansions being presented by Gontcharov and Hill in [2]. Using correlation techniques, a polar plot of *diffuseness*, or *correlation directivity*, can be produced. The extended concept of a *correlation map*, whereby correlation coefficients formed between direct and reflected sound are plotted as a function of listening position, was introduced by the authors in [3]. Readers not familiar with DML technology are referred to previous publications, for example [4][5][6].

In this paper, the authors wish to investigate the behaviour of the correlation directivity as a function of the reference direction.

2. CORRELATION DIRECTIVITY

Mathematical modelling and measurement were used to illustrate the concept of correlation directivity in a previous paper [1]. Example plots of measured correlation directivity are included in Figure 1 and Figure 2. The response of the loudspeaker at each direction is compared to that of a chosen reference direction using the cross-correlation function. The comparison may equivalently be made in the time or frequency domains. The maximum value of the normalised correlation is then plotted as a function of angle, having a limiting value of unity at the reference angle. The following equation uses Mathcad [7] functions to act on vectors X and Y, which contain the two impulse responses being correlated.

$$correlate(X,Y) = \max\left(\mathrm{Re}\left(ICFFT\left(\frac{\overline{CFFT(X)}\,CFFT(Y)}{\left|CFFT(X)\right|\left|CFFT(Y)\right|}\right)\right)\right)$$

The measurements plotted in Figure 1 and Figure 2 follow the suggested analysis, and indicate that the DMLs are more diffuse than a conventional loudspeaker. Each of these figures uses a different reference angle, namely 0°, 45°. The 0° case follows the original papers.

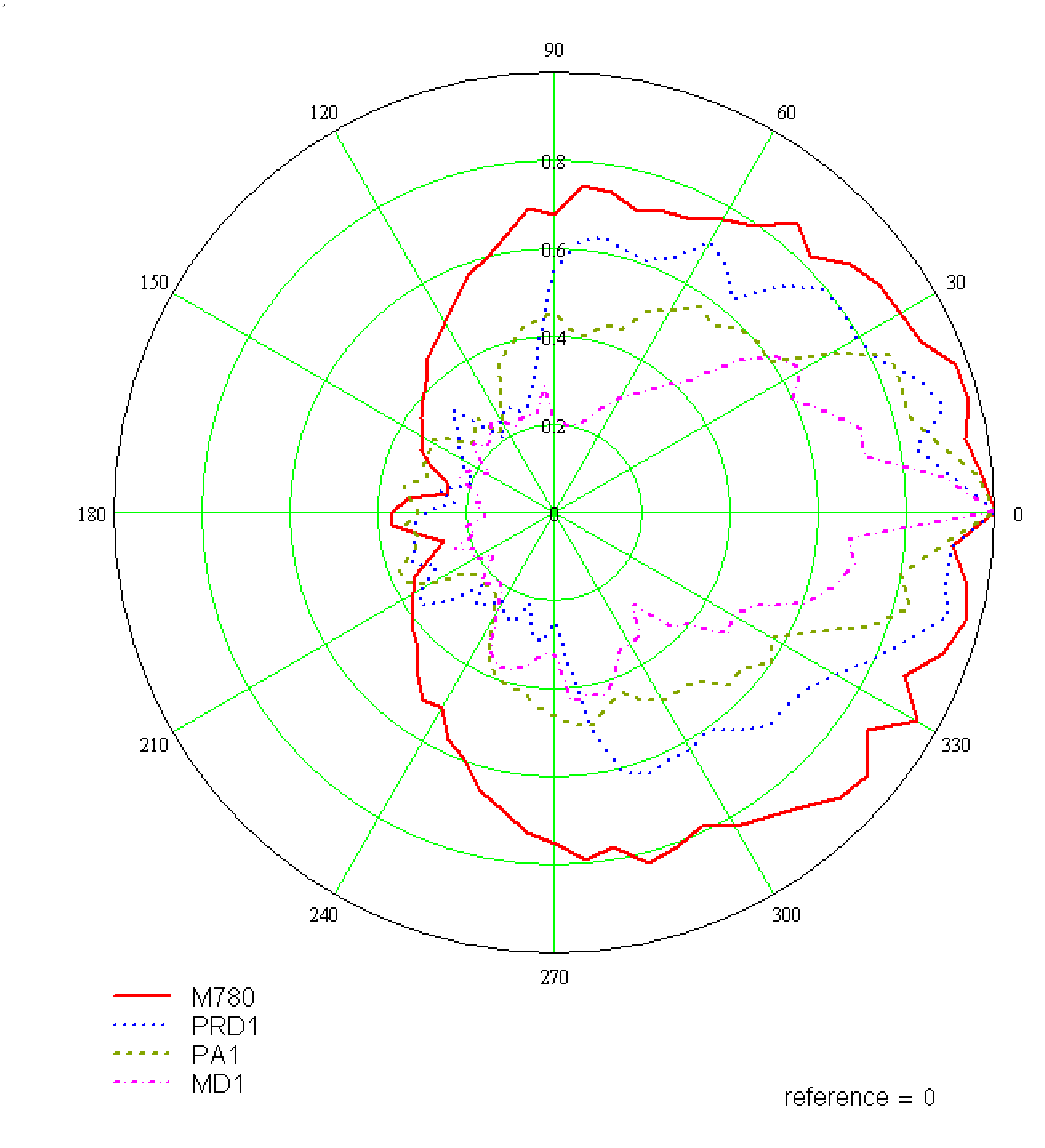

Figure 1. Correlation directivity plots for four loudspeakers, using 0° reference.

The M780 is a conventional, two-way book-shelf loudspeaker. The DMLs are of different size and material construction, and PRD1 and PA1 have multiple exciters. The exact details are proprietary, but all panels utilise a sandwich-type construction.

The PRD1 is used in commercial product, and has a similar area to standard A4 / Letter size paper, being about 26 cm x 23 cm. The PA panel is a prototype loudspeaker for small public address applications, and is A2 sized, i.e. about 59 cm x 42 cm. MD1 is a single exciter, demonstration DML which has been used as a source for several AES papers, including [1, 2, 3 and 8]. The MD1 has the almost the same area as the PA panel, being about 54 cm x 48 cm.

It should be noted that the conventional directivity and correlation directivity results were in no way connected, representing effectively orthogonal metrics of the loudspeaker – it is not possible to infer one from the other. A conventional loudspeaker (such at the M780 in Figure 1) produces a wavefront which shows strong correlation from angle to angle. Although the correlation is largely angle independent, the level is not. The DML is in some ways the dual case. It has a level directivity which is largely independent of angle (in a band-averaged sense) [8], but a correlation directivity which falls off with angle.

Therefore to properly characterise an arbitrary acoustic source, both level and correlation directivity are required. A similar measure could be used to characterise the reflections from a surface. It would differentiate between specular and diffuse reflectors, even if the conventional directivities of their reflections were the same.

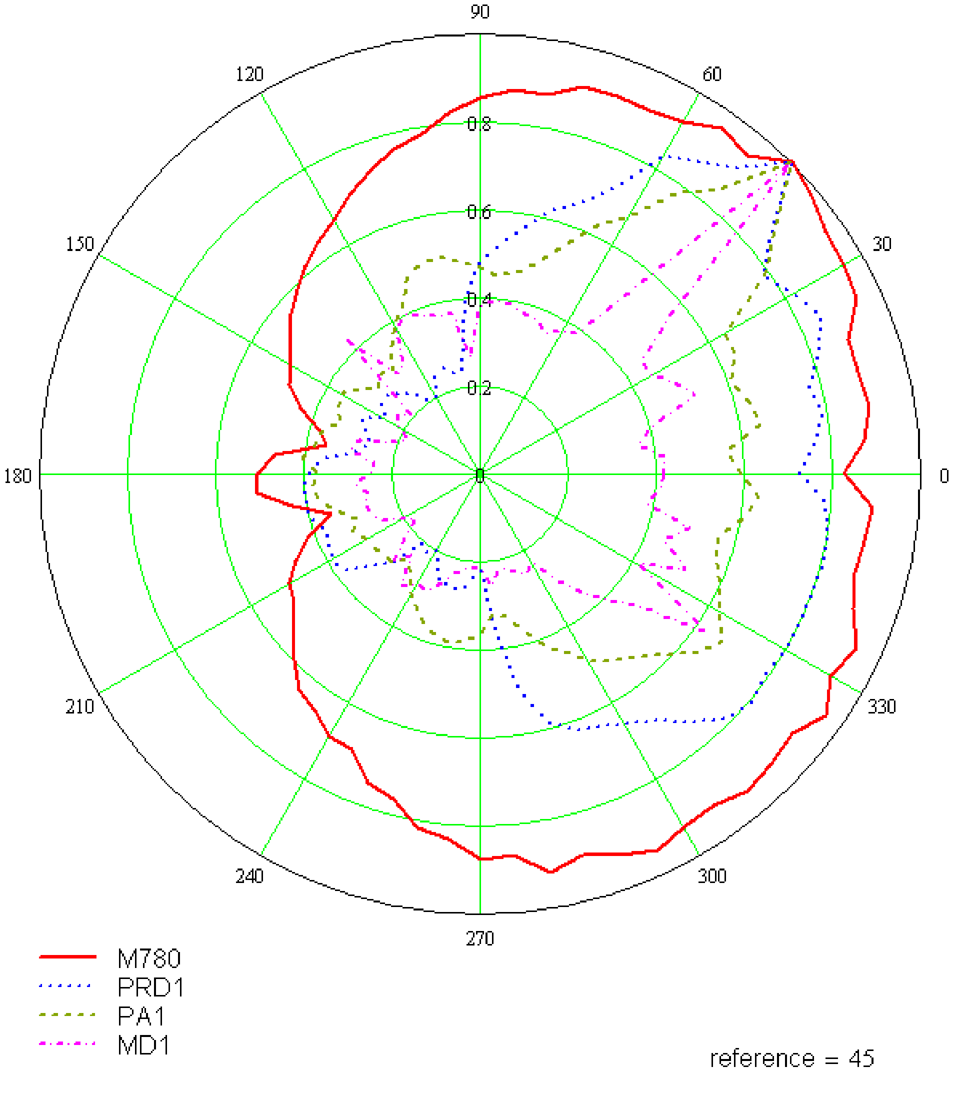

Figure 2. Correlation directivity plots for four loudspeakers, using 45° reference.

3. DIFFERENTIAL MEASURES

3.1. Spatial bandwidth

A visual examination of the correlation directivities above, shows that the rate at which correlation drops away from unity varies with both reference angle and loudspeaker. In this paper, the authors suggest possible objective measures of this behaviour – the spatial bandwidth of correlation. This could be defined in a number of ways, but in any case would be indicative of the rate at which the correlation coefficient falls from unity. Thus, one possible characterisation of the diffuse field would be to plot the spatial bandwidth of the correlation directivity as a function of the reference direction. Two alternative methods of calculating the spatial bandwidth are now presented.

3.2. Method 1 – inverse derivative

Noting that the spatial bandwidth is inversely proportional to the rate at which correlation falls from unity, one natural definition follows.

Spatial bandwidth = $1/(dr/d\theta)$

Where r = correlation coefficient, θ = angle.

The unit of spatial bandwidth is the same as the unit of angle used, e.g. degrees or radians.

Because differentiation is a noise-sensitive process, the results show strong fluctuations, the severity of which cannot be unjustified from the original data. A more noise-tolerant algorithm is therefore preferable.

3.3. Method 2 – 3dB bandwidth

This method is inspired by an observation from analogue filter theory. Consider a second-order low-pass filter of Butterworth form, where the power response is given by $|H(x)|^2 = 1/(1 + x2)$, $x = f/fc$. The cut-off frequency could be defined by the point at which the value of $|H(x)|^2$ reaches ½.

In order to improve the noise tolerance of the method, instead of using $|H(x)|^2$, we propose to use a two-sided method, i.e. $H(x)^* H(-x)$.

$$\beta \Rightarrow r(\theta, \theta + \beta)\, r(\theta, \theta - \beta) \le 1/2$$

Where β is the spatial bandwidth at angle θ. In some cases, this product may never drop below ½, so β has a limiting value of 180 degrees. The spatial bandwidth of the four loudspeakers is plotted in Figure 3, below.

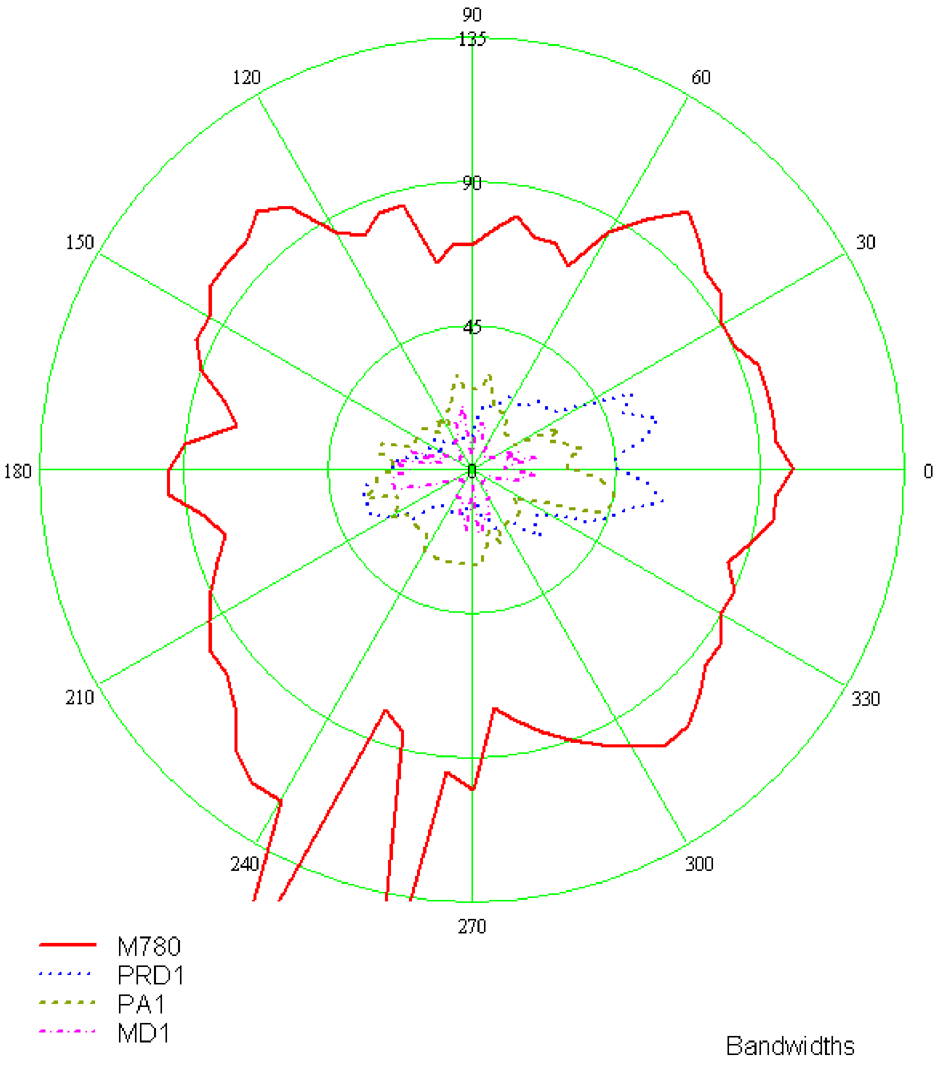

Figure 3. Spatial bandwidth vs. reference angle of loudspeakers by method 2

Source	Mean	Min	Max	Std. Dev.
M780	93.9°	65°	180°	18.1°
PRD1	24.8°	10°	60°	13.8°
PA 1	25.0°	15°	45°	6.8°
MD1	11.0°	5°	25°	5.9°

Table 1. Statistical summary of results

4. RESULTS

Using the results of the integration based method described in 3.3, and plotted in Figure 3, it can be seen that the conventional loudspeaker produces correlated acoustic radiation out to angles in excess of 90°. In contrast, each of the DML's acoustic radiation becomes significantly decorrelated after about 25°, or less. This angle is wide enough to provide a convincing stereo image, but narrow enough to avoid the problem of correlated early reflections. This observation helps to explain the results of psychometric testing on DML sources reported in [9] and [10] by Harris, Flanagan and Hawksford. The results from these series of tests confirmed the hypothesis that diffuse acoustic radiators, such as distributed-mode loudspeakers (DML), lessen the degradation caused by room acoustics on stereophonic localisation. In fact, the diffuse radiators performed significantly better than a quality two-way cone-in-box loudspeaker system even in the *sweet-spot* which, under anechoic conditions, could be assumed to favour the latter.

Mean values of spatial bandwidth are tabulated with other statistical quantities in Table 1 above.

5. FUTURE WORK

All the sources used in this work have a correlated component of their acoustic output. It is possible to eliminate this in a DML in certain circumstances. It would be interesting to characterise such a source by the methods outlined in this paper.

Just as the concept of correlation directivity for acoustic sources has be generalised to include correlation maps of acoustic fields, it would be possible to generalise spatial bandwidth in a similar manner, although the method of calculating this would present some challenges.

6. CONCLUSIONS

A concept of *correlation directivity* was reviewed and clarified. It was noted that the conventional directivity and correlation directivity results were in no way connected, representing effectively orthogonal metrics of the loudspeaker.

A new measure, the *spatial bandwidth of correlation*, was introduced and defined. Two alternative methods of calculating the spatial bandwidth were presented. The "3dB bandwidth" method was the more noise immune of the two. Results were presented for four different loudspeakers, including three DMLs. The different material properties of the DMLs produced different spatial bandwidths.

The ability to design a loudspeaker with a specified spatial bandwidth affords new and as yet unexplored opportunities.

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