DISTRIBUTED MODE LOUSPEAKERS: BEHAVIOUR AND MEASUREMENT

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1. INTRODUCTION

Distributed Mode Loudspeakers (DMLs) represent an established flat panel loudspeaker technology that has been widely discussed in the academic literature. Their main distinction from a conventional cone loudspeaker is that, instead of attempting to reproduce a point source through pistonic behaviour, this class of loudspeaker is inherently modal. The resonances of a plate capable of supporting bending vibration are excited at one or more locations and the resonances of the system balanced to produce a high quality loudspeaker.

The extension from a singe degree of freedom associated with a cone loudspeaker to the complex two-dimensional vibration of a DML opens up a range of possible effects over the frequency band. In particular, there is no one "reference" DML, rather a range of possibilities, determined by the demands of the application, both technical and commercial. The aim of this paper is to provide a broad outline of possible behaviours, focussing on the measurement methods that may be employed to characterise them.

2. FREQUENCY RESPONSE AND DIRECTIVITY

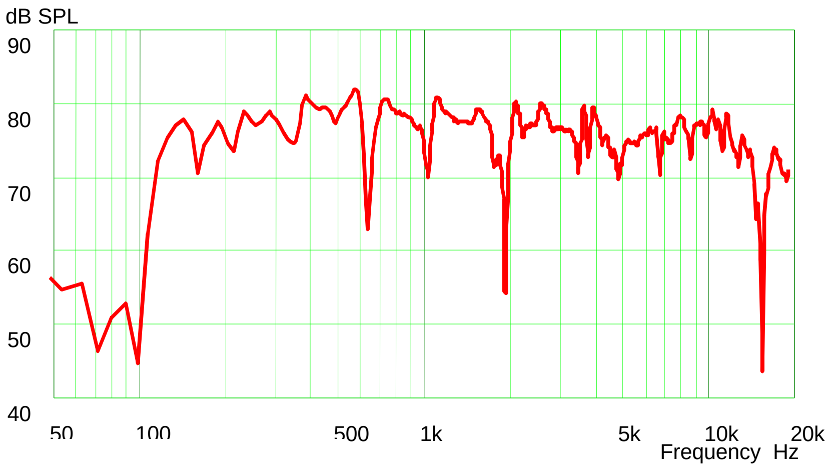

Figure 1: On axis SPL of a typical DML

Figure 1 shows the on-axis frequency response of a typical DML measured anechoically at 1m. This particular example was designed for integration with a sub-woofer in a TV application, and comprises a panel 400mm x 60mm, acoustically sealed in an enclosure 40mm deep. It is presented here as an example of a high quality design that has been optimised for a specific application, demonstrating a wide bandwidth of some 8 octaves.

The motivation for this paper, however, is to illustrate the range of possible behaviours that can be shown by a DML. Consequently, the choice of panel design has not been determined by the quality of sound output, rather to show such a range in a single device. The non-optimal design described subsequently is balanced by the response shown in figure 1 of a well-designed example.

The panel chosen for the purposes of this paper is comprised of the following construction.

Material:	composite, resin impregnated paper honeycomb
Panel length	500mm
Panel width	350mm
Panel exciter	electrodynamic, 25mm diameter voice coil, 4 ohms
Acoustic sealing	open back dipole

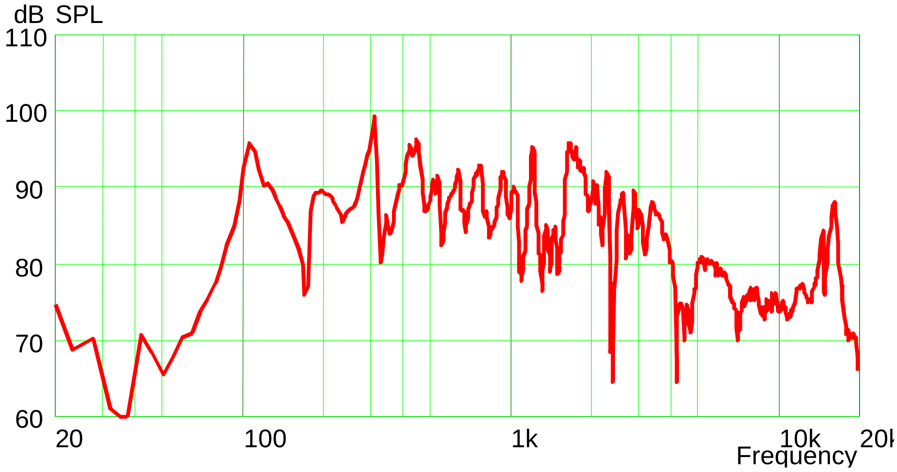

Figure 2: On axis SPL as a function of frequency at 1m, 2.83Vrms

Figure 2 shows the on-axis pressure as a function of frequency, measured anechoically at 1m, at 2.83V rms. The fundamental resonance of the system is clear around 100Hz, below which the SPL decreases rapidly into the measurement noise floor. Above the fundamental resonance the response shows increasing complexity, fluctuating rapidly on a narrow band frequency scale. The source of this fluctuation is the complex modal behaviour of the loudspeaker and the root of this increasing complexity is two-fold. Firstly, as the frequency increases, higher order panel modes are excited and the density of modes increases. Secondly, the acoustic radiation results from an interference of the radiation from all modes below the excitation frequency. This is in contrast to the velocity response of the plate, which is dominated by the modes at this frequency. Moving into the acoustic domain gives more equal weight to the modes below the excitation frequency, and the relative phase of these modes gives rise to a cumulative increase in the complexity of the frequency response.

At the high frequency end of the graph, a clear single resonance is evident. This is often referred to as the "aperture effect" and is associated with the size of the driving voice coil with respect to the bending wavelength. This is described in more detail later, with more measurements that illustrate the effect. This feature and the general loss in high frequency energy are examples of the non-optimal design chosen for this exercise. The aperture resonance is generally controlled in the design process and can be usefully employed to extend the high frequency bandwidth, where other parameters are non-optimal through application or commercial constraints.

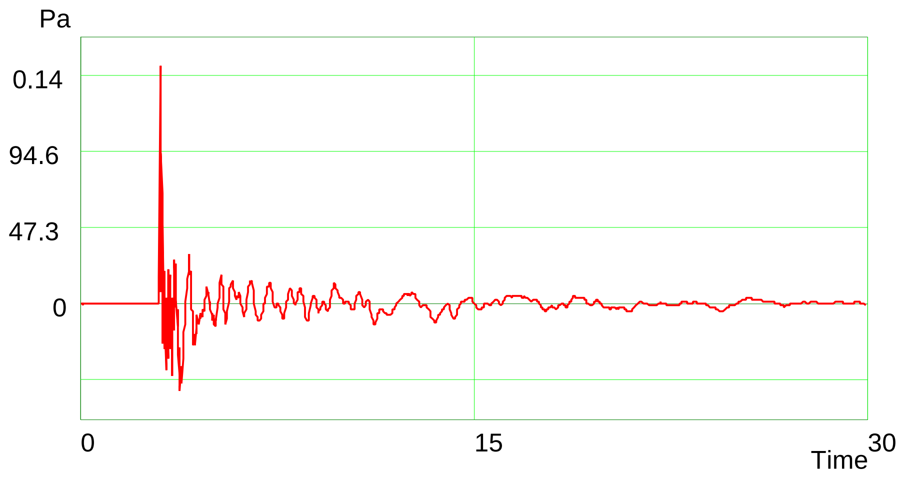

Figure 3: On axis SPL as a function of time at 1m, 2.83Vrms

The impulse response, shown in figure 3, is characterised by a sharp transient as the energy is transferred from the exciter to the panel. This is followed by a reverberant tail as the energy disperses into the panel forming a complex superposition of modes. This characteristic shape is responsible for some of the subjective performance of DMLs. The transient response is not only localised in time but also in space, emanating from the area close to the exciter position. This signal allows the localisation of a stereo image[1] both from separate DMLs and also from two exciters spatially separated on a single DML panel. The reverberant tail that follows the initial impulse quickly looses any correlated structure, which reduces any perception of ringing associated with the time constant of energy decay.

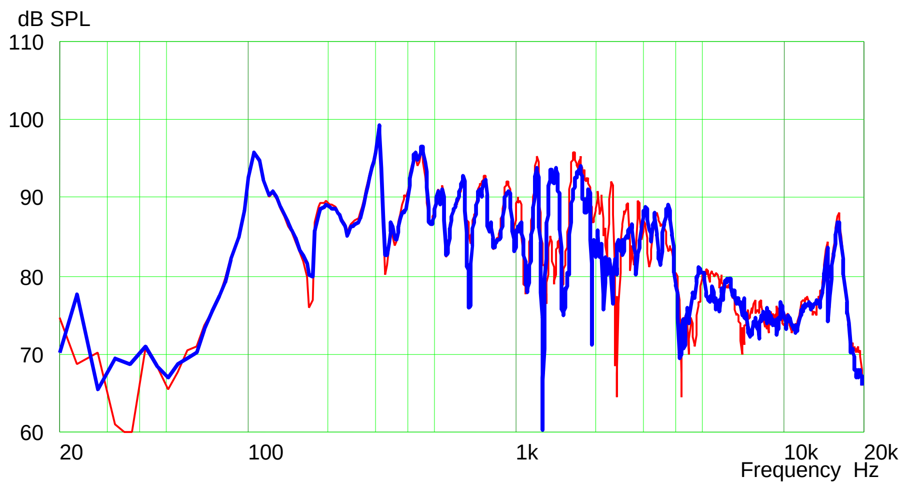

Figure 4: SPL as a function of frequency at 1m, 2.83Vrms. Red: on-axis response. Blue: 10-degree off-axis response.

Figure 4 shows two measurements of frequency response. The first is the on-axis response from figure 2, the second was measured 10-degrees off axis. At low frequency, where the acoustic wavelength is large compared to both the panel size and the bending wavelength, the directivity is a smooth function of angle and the two traces closely match. As the frequency increases into the densely modal range the behaviour changes markedly. The radiation from each mode starts to show significant angular dependence. The acoustic output from all modes below the driving frequency sum up with complex phases to yield a complex directivity pattern that shows significant fluctuation on a small angle scale.

This narrow band fluctuation of the response both in frequency and angle is further shown in figure 5a, where polar diagrams of the low frequency response and the response in the densely modal range are presented. The level of detail in this response contrasts with a typical measurement of a cone loudspeaker, where the response is generally smooth as a function of angle and frequency. Quantification of this fine structure is readily possible with an automated measurement system, however the large quantity of data that this generates can be cumbersome and difficult to draw conclusions from. An alternative is to quantify the response on a broad scale and to separately quantify the fine structure. Such an approach is now outlined.

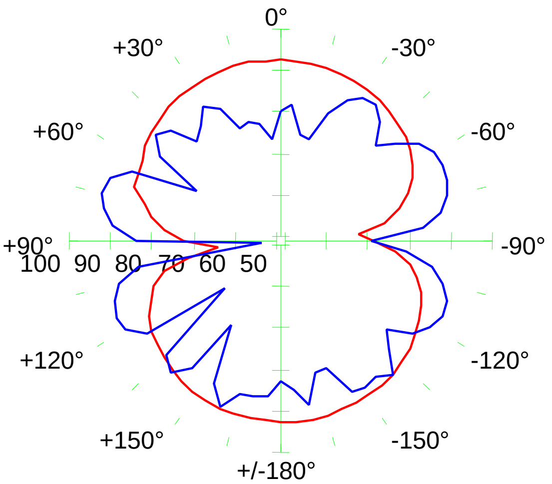

Figure 5a: Directivity plot of SPL, measured at 1m, 2.83Vrms. Red: response at 100 Hz. Blue: response at 4kHz.

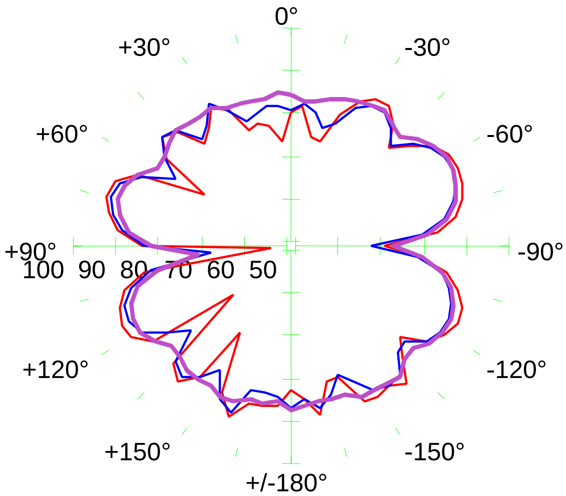

Figure 5b: Directivity plot of SPL, measured at 1m, 4kHz, 2.83Vrms. Red: narrow band data. Blue: third octave smoothed data. Purple octave smoothed data.

Figure 5b shows plots of directivity in the densely modal range, where the narrow band data is overlaid by third octave and octave smoothed data. It is clear that the frequency-smoothed response is a more suitable measure of broad energy distribution than the narrow band response, yielding a smooth trace as a function of angle.

The directivity of a DML may be controlled by a number of parameters including the material of composition. The directivity plots shown in figure 5 show a uniform directivity response, when averaged over an octave band. Figure 6 shows a directivity plot at 10kHz, where a change in behaviour is obvious, and the directivity shows additional energy beamed off-axis. This feature is a consequence of the propagation velocity of bending waves relative to the speed of sound in air, and is often referred to as the coincidence effect. The frequency above which the directivity is modified in this manner, which corresponds to matching of the two wave velocities, is known as the coincidence frequency.

The directivity shown in figure 6 is controllable through the design parameters of the DML. In particular the panel material may be chosen to either include this effect in the operating band or shift it beyond the high frequency limit of the loudspeaker. In some applications this directivity may be beneficial, giving rise to enhanced room coverage in the high frequency band, and a corresponding improvement in intelligibility. This effect is in contrast to a conventional pistonic source where the directivity generally narrows at high frequency.

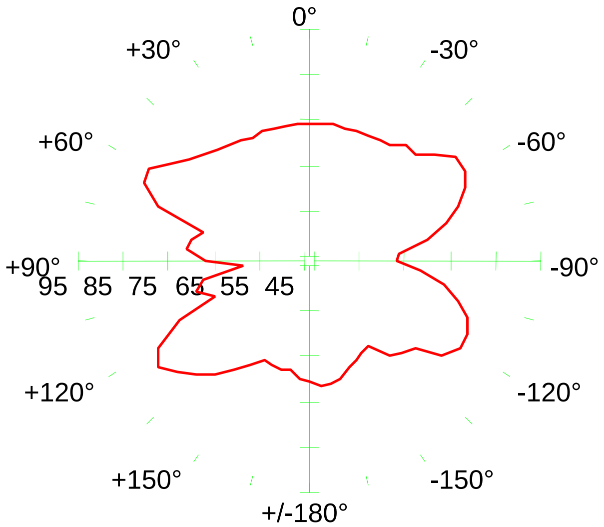

Figure 6: Directivity plot of SPL, measured at 1m, 2.83Vrms, 10kHz.

The measurement of the frequency response may also be made less sensitive to the fine structure of the response by spatial averaging. One of the most appropriate measures is the acoustic power radiated from the device, which may either be measured by a reverberant method or, as shown in figure 7, summed up from the polar response data. The acoustic power shows a smoothing of the frequency response fluctuations, and is more representative of the integrated response of the loudspeaker in a room. Measurements of acoustic power applied to DMLs are described in detail in Gontcharov[2] *et al.* and Ferekidis[3]. Ferekidis shows how measurements of acoustic power summed over 3 separate angular ranges yield a set of frequency response traces that in combination provide a powerful design tool.

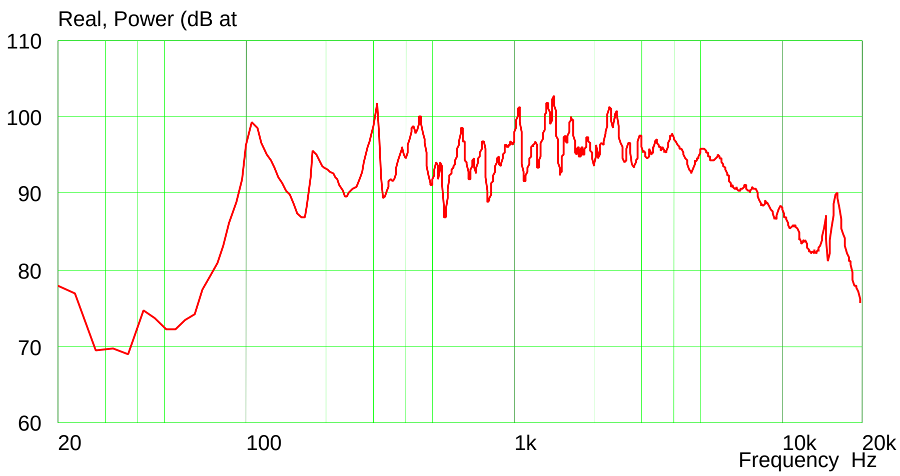

Figure 7: Acoustic power calculated from a weighted sum of the polar response data.

In summary, the radiation field from a DML has been discussed and a number of features including the fine structure of the response have been presented. It has been shown that in order to quantify the energy distribution of a DML, single point measurements and narrow band frequency measurements exhibit a level of detailed structure. In contrast, directivity plots of the frequency-smoothed response and measurements of acoustic power quantify the response on a more useful level for design purposes.

3. THE DIFFUSE SOUND FIELD

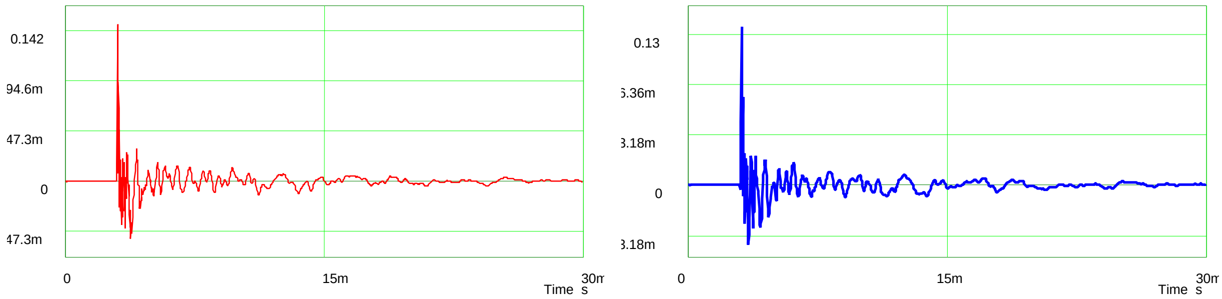

Figure 8: Impulse response measurements on-axis (red) and 30 degrees off-axis (blue).

The fine structure of the acoustic response may alternatively by viewed in the time domain as shown in figure 8, where the on-axis and 30 degree off-axis responses are presented. Although broadly similar, the detail of these responses are not well correlated. This feature corresponds to a break in spatial correlation of the response and is the origin of the diffuse sound field. The diffuse sound field radiated by a DML has been widely reported and can give rise to improved performance in situations sensitive to strong boundary reflections. Here the break in correlation between reflections, generally emitted at different angles, means a less severe interference, reducing effects such as comb filtering[4].

The quantification of correlation is carried out by means of the cross correlation function, the maximum value of which gives a measure of correlation that is robust to arbitrary small delays (measurement distances) between the responses. The correlation level of the impulse responses shown in figure 8 is 0.43, indicating a significant level of decorrellation. Further detail may be gained when the correlation is plotted as a function of angle, as shown in figure 9. Here a reference position, the on-axis position, is chosen and the correlation of all angles with respect to this position is plotted. The on-axis point on the graph is unity, corresponding to the maximum value of the autocorrelation function. As angular separation from the reference point increases, the correlation quickly decreases showing the diffuse nature of the sound field. It should be emphasised that the polar plot of correlation does not include information on the energy distribution. The measure of correlation quantifies the level of diffuseness, and is complementary to conventional measures of energy distribution.

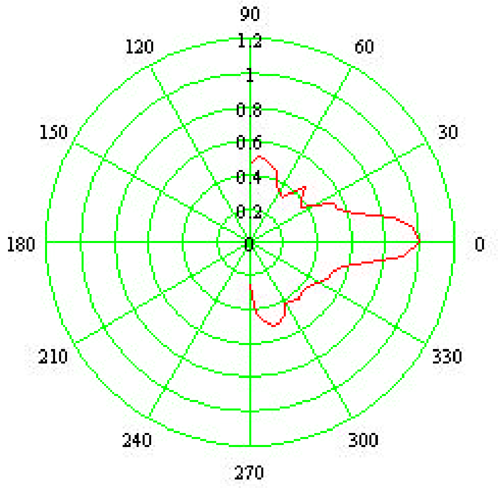

Figure 9: Correlation polar response

The level of correlation shown in figure 9 may be averaged to give a single measure of spatial correlation. In addition frequency resolution may be obtained by initially filtering the data into octave bands. Figure 10 shows such a measure of average correlation as a function of frequency. At low frequency, where the response shows a smooth dependence on angle, the average level of correlation is high. As the frequency increases into the densely modal range and the complexity of the response increases, the levels of correlation are reduced, indicating significant levels of diffuseness.

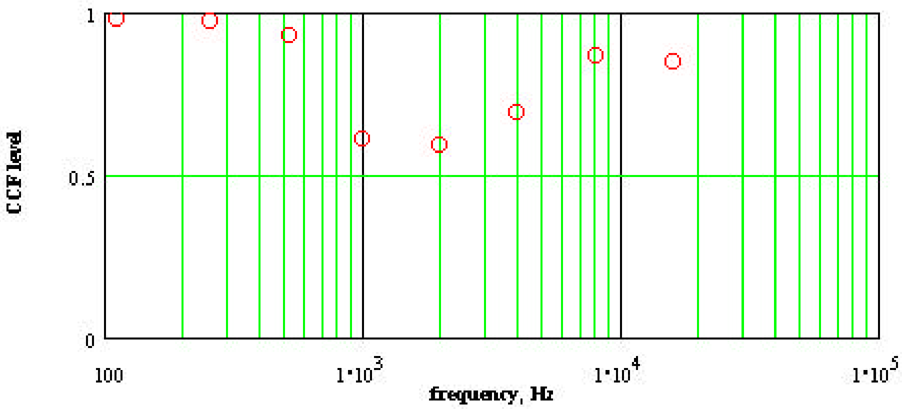

Figure 10: Frequency dependence of the average correlation.

As the frequency is increased still further the correlation levels rise. This rise in correlation is a consequence of the aperture effect introduced earlier. This effect originates from a matching between the voice coil dimensions and the bending wavelength, which act to limit the energy propagated into the panel. Instead, the vibration of the panel is focussed on the region of excitation and the directivity looses its complex dependence on angle, demonstrating a behaviour similar to a conventional point source.

The graph shown in figure 10, and subsequent discussion illustrate the power of correlation in the quantification of a diffuse sound field and its use to inform the underlying behaviour. The levels of correlation may be controlled by the design of the DML in a number of ways. Firstly, a number of techniques have been developed to address the aperture resonance, including the choice of the panel material, voice coil size, and the application of damping. Secondly, the broadband level of correlation is determined by the size and shape of the loudspeaker, the excitation method and position. In addition, the damping of the panel has a direct consequence on the levels of correlation. An increase in damping serves to increase the spatial correlation, reducing the level of diffuseness. Damping may be applied through the panel material properties or alternatively the boundary conditions and supporting method.

In summary, a measure of the spatial correlation has been outlined. This has been shown to quantify the fine detail of the DML acoustic response. Depending on the details of the design, typical DMLs can show significant levels of decorrellation (<0.5) persisting to high frequency or alternatively remain well correlated over the whole operating bandwidth. Such a range emphasises the point made earlier that there is no “reference” DML response. The development of the correlation method is described in detail by Gontcharov[4] *et al*, where several DMLs are compared and a conventional cone loudspeaker is also presented.

4. DISTORTION

The sources of DML distortion are very similar to cone loudspeakers. The panel itself generally operates well within its linear region and the motor is the main source of distortion. For electromagnetic motors, conventional design parameters such as magnetic circuit linearity, thermal compression, and spider non-linearity control the levels of distortion.

When measuring distortion care should be taken because of the complex frequency response and directivity; this is particularly relevant for distortion measurements where single frequency excitation is often used. A setup where a DML is excited at a fixed frequency and THD is measured anechoically at a single point is prone to complications. Fluctuations that may be present in the frequency response can strongly modify the fundamental and harmonic spectrum in a manner that is not representative of the total sound field.

In many ways the measurement of DMLs for distortion poses the same challenges as the measurement of a sub-woofer in a room. The modal response of the room is convolved with the sub-woofer response and spatial averages of distortion are required. Similarly, when measuring DMLs, it is advisable to average the results spatially and over frequency yield representative results.

5. IMPEDANCE

The electrical impedance the DML under test is shown in figure 11; the graph displays a broadly constant response up to 1kHz, followed by an inductive rise. The system modes are clearly visible on the impedance trace, which result from the back emf generated in the motor system. The presence of these modes is a useful diagnostic tool, particularly when correlating features in the acoustic response with strong modes excited in the panel structure.

The use of an impedance trace for the determination of Theile-Small parameters is standard practice for cone drive units. With DMLs the complex interference of many system modes prevents the use of models based on a single mass-spring resonance. Instead the Theile-Small parameters of the motor should be measured without the panel attached, in which case standard methods and measurement equipment may be applied.

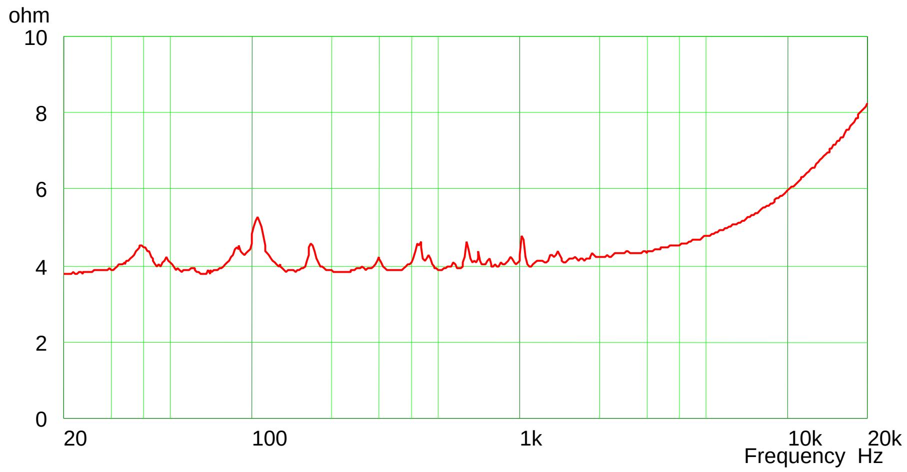

Figure 11: electrical impedance

6. CONCLUDING REMARKS

In conclusion, Distributed Mode Loudspeakers offer a high quality solution for sound reproduction, as demonstrated at the beginning of this paper. This class of loudspeaker opens up a range of possible behaviours over the frequency spectrum, determined by the details of the design. A non-optimal DML has been chosen to illustrate a number of these effects in a single device, and a suite of measurements has been presented.

The complex nature of the sound field, responsible for the operation of the DML as a diffuse source, has been described. In order to quantify the energy distribution of the radiated sound field, measurements of directivity and frequency response have been presented. It has been shown how frequency smoothed measurements of directivity and frequency responses of acoustic power quantify the energy distribution on a useful level. Spatial correlation has been presented as an appropriate measure of the diffuseness, together with a discussion the design parameters affecting this property.

7. REFERENCES

1. NJ Harris and S Flanagan, "Stereophonic Localisation in Rooms, comparing the Distributed Mode Loudspeaker (DML) with conventional two-way cone-base loudspeakers", Proceedings of RS14 (1998)

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4. V Gontcharov, and NPR Hill, "Diffusivity Properties of Distributed Mode Loudspeakers", Proceedings of AES 108th Convention, Pre-Print #5095 (2000)