The Distributed Mode Loudspeaker – Theory And Practice

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A theoretical model of the distributed mode loudspeaker (DML) is presented, and compared to that of a conventional, mass-controlled loudspeaker. Electromechanical modelling results are compared to real measurements of example DMLs. The implications of uniform directivity and diffuse radiation to room interactions are discussed.

1 HISTORY

From the 1920's the perfect loudspeaker was conceived to operate like an ideal piston. Whether the loudspeaker diaphragm was driven from a moving armature, or later on a moving coil, the aim was to control the sound radiated by as pistonic a motion as possible.

By operating this diaphragm as a moving mass sets two requirements to maintain an even frequency response. The first is that the diaphragm has to be small enough to approximate to a point source. A point source with constant acceleration (gained from its mass-controlled operation, with constant force) gives a flat frequency response. The second requirement is that the diaphragm all moves with the same acceleration, that is the diaphragm behaves like a piston.

This presupposes a radiator size that is small compared to the wavelength being reproduced, and immediately leads to the requirement for two or more diaphragms to cover 3 or 4 octaves. It also means that the diaphragm has to be quite rigid over the frequency band it is trying to reproduce.

More difficulties arise when we consider that as much energy leaves the back of the diaphragm as the front, and since the source is coherent, it is reversed in phase. Leaving the rear to radiate freely will automatically produce a dipole radiator, with interference between back and front, and a loss of output at low frequencies. Although dipoles have been used in special circumstances for their audiophile qualities in respect of cabinet colouration, the on-axis SPL falls at 6dB per octave below cut-off.

For all practical purposes then, this means we have to absorb the rear radiation inside a cabinet of some kind. Cabinet panel modes, standing waves and diffraction all conspire to defeat our attempts at making a success of this venture.

2 THE DISTRIBUTED MODE LOUDSPEAKER

The distributed mode loudspeaker (**DML**) is an acoustic radiator whose electrical, mechanical and acoustical properties differ completely from traditional moving coil types, that it represents a new class of loudspeaker.

A **DML** is identified by the fact that its radiation is due to uniformly distributed, free vibration in a stiff, light panel and not to pistonic motion. To understand its operation, a mechanical model of the operation is first derived, from which an equivalent circuit can be developed. With this equivalent circuit it is possible to model the resulting velocities and displacements of the various elements.

3 THEORY

Because bending waves are dispersive (the wave velocity is a function of frequency) [1], a good approximation is to consider the panel as a randomly vibrating area. The radiation intensity from such an area is shown in Morse & Ingard [2] to depend on the square of the mean velocity, and hence the requirement is for constant velocity. In order to achieve this constant velocity with a constant force, the mechanical impedance must be resistive. A panel operating in bending waves meets this criterion [3]. Expressions for bending wave velocity and mechanical impedance are quoted below,

$$v(\omega) = \sqrt{\omega\sqrt{\frac{B}{\mu}}} \qquad (1)$$

$$Zm = 8\sqrt{B\mu} \qquad (2)$$

where;

B = bending rigidity of panel, Nm
μ = mass per unit area of panel, kg/m2
Zm = mechanical impedance of panel, kg/s
ω = angular frequency, rad/s

3.1 Mechanical model

In order to develop a model of any physical system, it is necessary to make some assumptions. Because we are considering the DML to be randomly vibrating, the existing motion of the panel will be uncorrelated to any new input being applied, and therefore it looks like an infinite plate. Additionally, because the panel has low mechanical loss, we can assume that all the energy supplied to the panel had to be dissipated by acoustic radiation. These assumptions have been shown to give useful results, and measurements confirm that the radiated pressure is proportional to the mean velocity in the panel. Thus, to calculate the radiated acoustic power, we need only to calculate the mechanical power delivered to the panel. Likewise, the mean sound pressure can be found from the mean panel velocity.

Given that the DML is a resistance-controlled device, and that the acoustic radiation need be considered in detail, we can develop an equivalent circuit from consideration of the mechanical components. The basic mechanical arrangement for an inertial magnet drive system is shown in Figure 1, and is taken from the nxt white paper [4], and further developed by Harris & Hawksford [5].

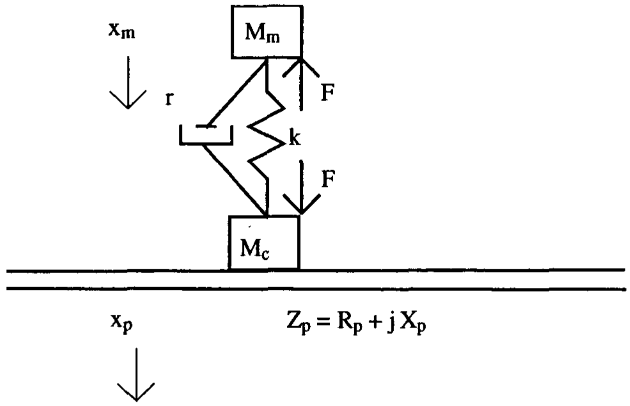

Figure 1 Basic mechanical arrangement

The magnet assembly is connected to the panel by way of a suspension, of stiffness k. A dashpot provides some resistive damping, r. Since the magnet is inertial, the force F acts on both the magnet mass Mm, and the coil mass Mc, in opposite directions. The coil is rigidly fixed directly to the panel, whose impedance is given by Zp.

3.2 Developing the equivalent circuit

Ideally, an electromechanical model, which will enable acoustic engineers to use familiar software modelling tools, is needed. This will allow the application of DML technology to any specific acoustic. Given that a stiff, light panel can be designed to have optimal modal distribution and low loss, it has been shown that in order to model the acoustic pressure or acoustic power, it is only necessary to calculate the mean velocity in the panel.

The mechanical model can be transformed into an equivalent electrical impedance circuit by a method proposed by Bauer [6]. The method uses the voltage-force-pressure analogy, called EFP for brevity. Mechanical structures and motions have magnitudes and directions, i.e. vector quantities, whilst electrical potentials and currents in a circuit are scalar. To be able to use electrical circuits to model motion, therefore, we need to restrict the analysis to motion in one axis. The mechanical network components that are used are shown in Figure 2, Figure 3 & Figure 4, along with their respective equivalent electrical components.

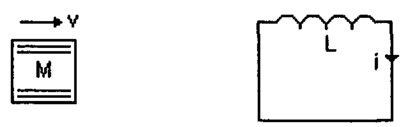

Figure 2 Electrical component analogue for mass

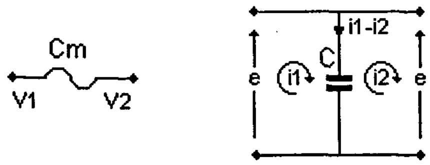

Figure 3 **Electrical component analogue for compliance**

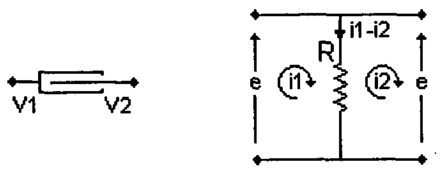

Figure 4 **Electrical component analogue for damping**

In considering the basic inertial drive for a **DML** panel, we can use these analogues to construct a complete equivalent circuit, and thereby determine the velocity characteristics of the loudspeaker. The mechanical arrangement is redrawn in Figure 5.

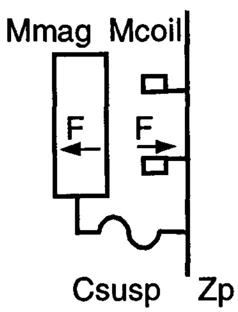

Figure 5 **Mechanical arrangement for inertial drive DML panel**

Translation into the electrical analogue can be done in various stages, shown in Figure 6, Figure 7 and Figure 8.

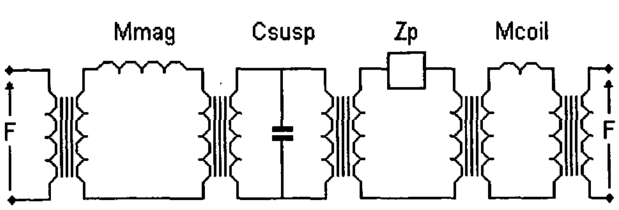

Figure 6 **Transformer coupled electrical impedance analogue**

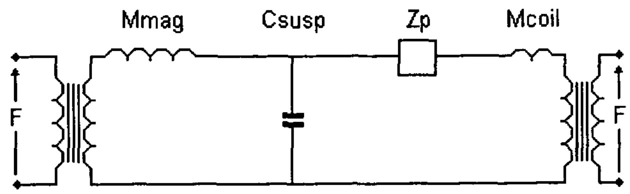

Figure 7 **Internal coupling transformers removed**

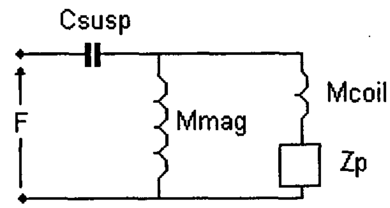

Figure 8 **Electrical impedance analogue, with all transformers removed**

It is, of course, now possible to transform this mechanical analogue into the electrical domain and solve for the variables, thus deriving the current in the panel. This solution method has been employed by Tashiro et al, [7] for calculation of the terminal impedance, mechanical impedance at the driving point and mean panel velocities.

3.3 Electromechanical modelling

In order to evaluate the variables in the analysis, the complete electromechanical circuit is coded into AkAbak ® [8], a commercially available electroacoustic simulator. The electrical and mechanical domains are constructed from the mechanical equivalent circuit shown earlier, with the addition of the transfer characteristics of the moving-coil exciter.

These parameters include the magnet moving mass, compliance, Bl factor and voice-coil DC resistance.

Coding takes place via a text-input file, based on the complete electromechanical circuit shown in Figure 9. A small amount of resistance Rs, has been added to model the suspension damping. Examination of this schematic shows that the velocity in the panel, and hence the pressure, is governed at low frequencies by the values of Cs and Mmag, acting as a high-pass filter. Values for these components are chosen to match the panel mechanical impedance Zp.

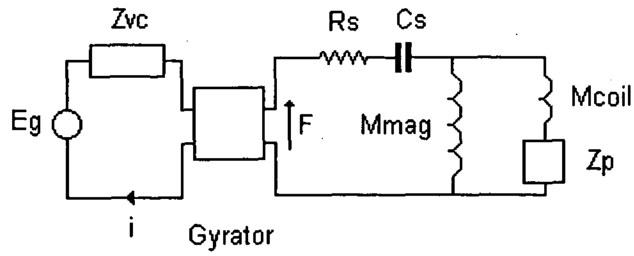

Figure 9 Complete electromechanical schematic for a DML panel and exciter

At high frequencies the velocity is governed by the coil mass, Mcoil, and the value of the panel impedance, Zp. Whilst Zp is substantially resistive for the most part, it has the general form shown in Figure 10.

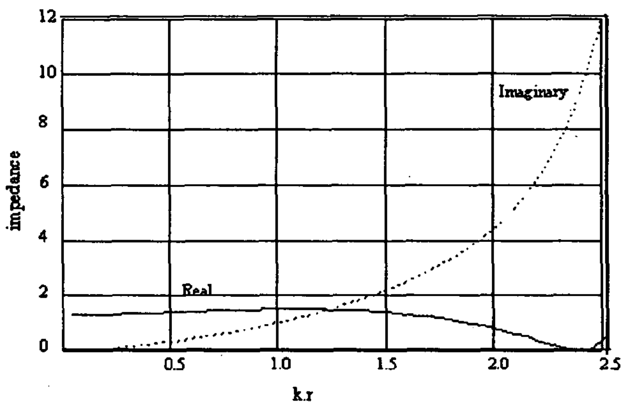

Figure 10 Typical panel impedance presented to the driving point

Indeed, at low frequencies the panel appears resistive, but at higher frequencies the reactive part becomes dominant. The combination of the mechanical impedance of the panel, which can be adjusted to suit any particular application, the coil mass and coil inductance determines the high frequency limit.

3.4 Modelling results

Solving the above circuit enables the mean driving-point velocity, and hence sound pressure to be evaluated. The following results were obtained from such a model.

3.4.1 Bl

In traditional loudspeakers the moving mass of the diaphragm presents a reactive load to the driving force, and when changes are made to the Bl factor of the magnet/voice-coil system then the whole low frequency performance is affected. This is illustrated in
Figure 11.

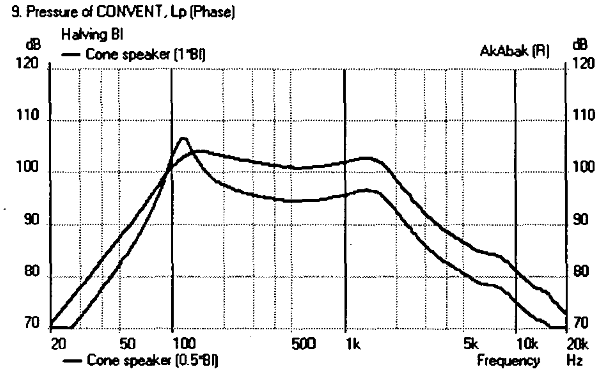

Figure 11 Traditional moving coil loudspeaker SPL, when Bl factor is halved

In the case of a DML panel the load presented to the driving point is resistive, so changes to the Bl factor, for example just change the broadband output level of the loudspeaker, as illustrated in
Figure 12.

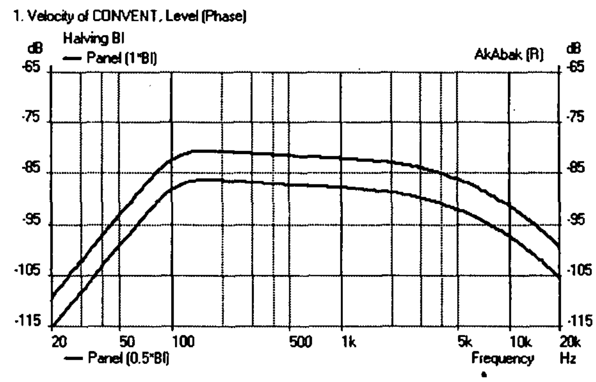

Figure 12 DML loudspeaker mean panel velocity, when Bl factor is halved

3.4.2 Terminal impedance

The reactive nature of the traditional moving mass loudspeaker is reflected in the terminal impedance, giving a classical low frequency electrical resonance. Since the DML panel is resistive, this is reflected in a flat terminal impedance curve. The two are compared in
Figure 13.

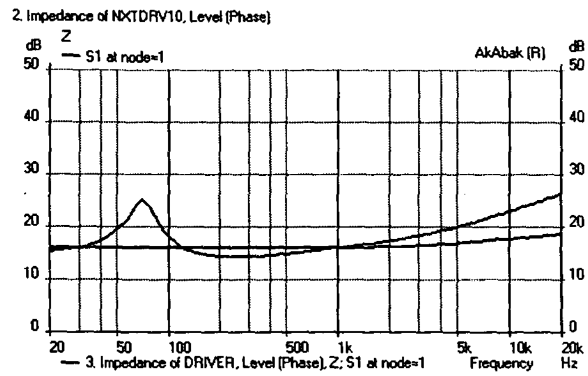

Figure 13 Comparison of Traditional loudspeaker terminal impedance, versus DML panel

3.4.3 Measured performance

Apart from the predictions from the impedance analogue, a number of measurements are shown in this section, to illustrate the various performance characteristics of **DML** panels.

3.4.4 Diffuse radiation

Because the **DML** panel is modal, the radiation that arises is diffuse and uncorrelated. This diffuse nature can be seen in the impulse response, as shown in Figure 14. Although the impulse response, shown in lasts for more than some 25 milliseconds, it has a random characteristic, with no single frequency that can be picked out.

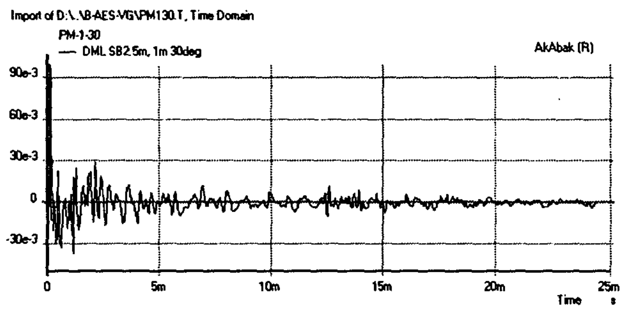

Figure 14 Typical impulse response of a DML panel, includes a first room reflection at 12 milliseconds

Transforming this impulse into the frequency domain gives the response as shown in Figure 15.

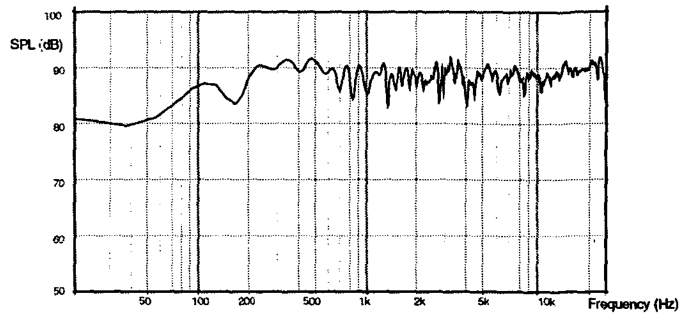

Figure 15 Typical unsmoothed frequency response of a DML panel

3.5 Directivity

Traditional loudspeakers have a narrowing directivity pattern with increasing frequency, typically requiring at least two drive units to cover the audible band. The beaming for a single, 20cm diameter drive unit is shown in Figure 16.

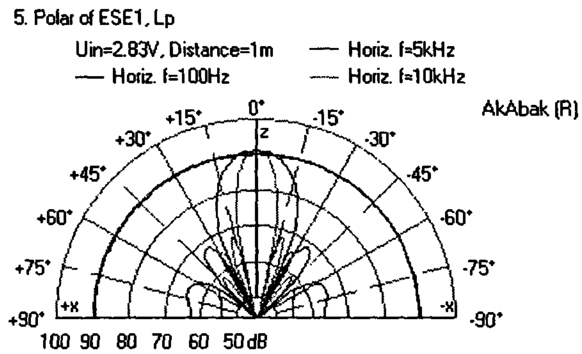

Figure 16 Typical polar response for a 20 cm drive unit

For **DML** panels the directivity is substantially independent of frequency as shown at 300Hz, in Figure 17. Because of the nature of the radiation, this directivity is maintained at 8kHz, as shown in Figure 18.

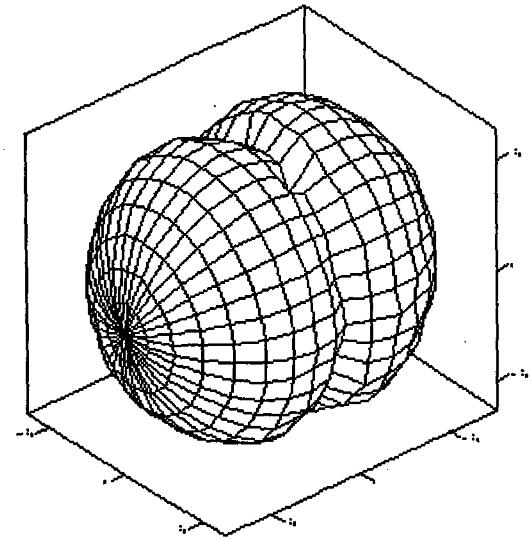

Figure 17 3D polar response (smoothed) of 0.3 m^2 DML panel, 300Hz

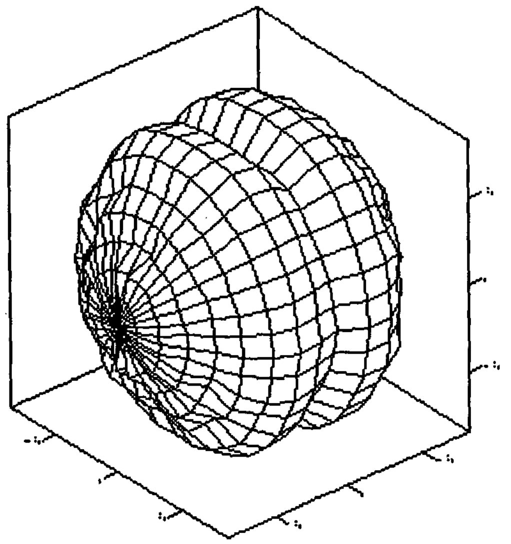

Figure 18 3D polar response (smoothed) of 0.3 m^2 DML panel, 8kHz

The panel is orientated such that the plane of the panel coincides with the circumferential dip in the polar response.

3.6 Room interactions

Because of the diffuse nature of a **DML** panel there exists a region close to the panel in which the pressure remains substantially constant. When in rooms the **DML** panel can use the rear radiation to support the front pressure region in such a way as to increase the region where the pressure remains constant. Since the **DML** panel has diffuse radiation, it also must enjoy diffuse reflections, illustrated by Azima & Harris [9].

These two features combine to give a loudspeaker that excites far fewer room modes than a traditional loudspeaker. To illustrate this advantage measurements have been made by Colloms and Ellis [10], using a traditional loudspeaker in a room, as shown in Figure 19, in comparison to a DML panel in the same room, as shown in Figure 20.

Measurements were made at a matrix of points within the room, with a sinusoidal input to each loudspeaker, at 250 Hz.

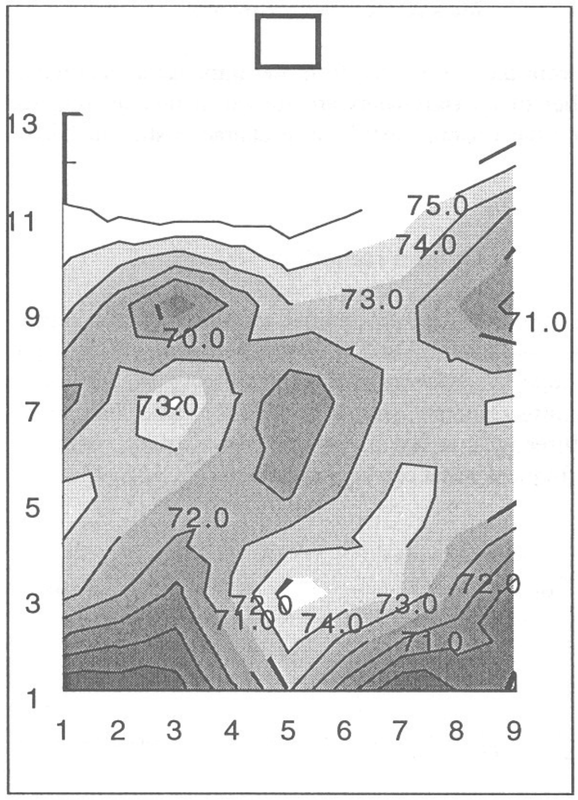

Figure 19 Room pressure contours from traditional loudspeaker, positioned at front centre

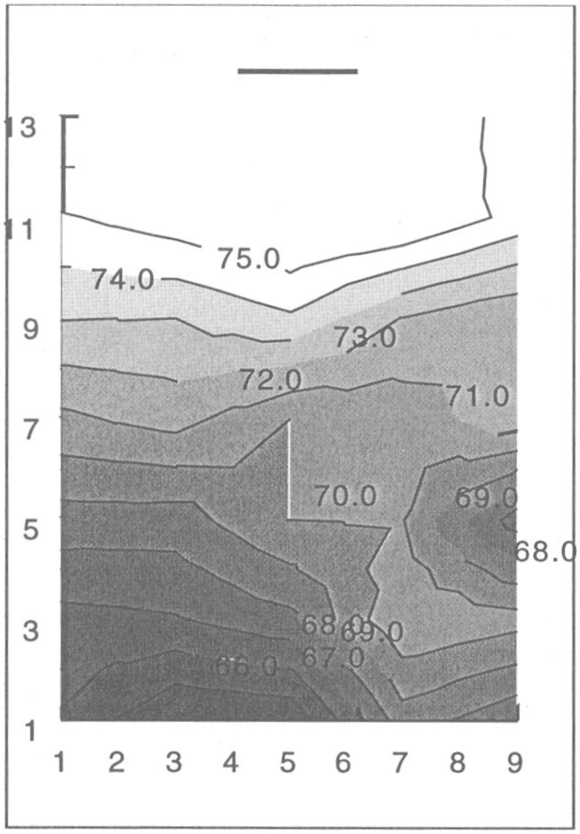

Figure 20 Room pressure contours from DML panel, positioned at front centre

4 CONCLUSIONS

A **DML** loudspeaker is, intrinsically, a broadband acoustic radiator. It is amenable to prediction and analysis in the same way, using similar tools, as traditional loudspeakers. It has a number of features that are useful to loudspeaker engineers, some of which include:-

- Wide bandwidth from a single radiator
- Temporally & spatially diffuse sound radiation
- Directivity & polar pattern - substantially frequency independent
- Intrinsic scalability
- Uncorrelated, constructive rear radiation, requires no enclosure
- Power loss versus distance - less than 6 dB/octave for certain boundary conditions
- Improved room interaction flat power, with no hot-spots
- Simple resistive load presented to the amplifier

5 REFERENCES

1 **P. M. Morse**, *'Vibration and Sound'*, pp 115-116., McGraw Hill.

2 **Morse and Ingard**, *'Theoretical Acoustics'*, Section 7.4., McGraw Hill.

3 **Morse and Ingard**, *'Theoretical Acoustics'*, Section 5.3.19., McGraw Hill.

4 **nxt white paper**, (C) New Transducers Ltd., 1996.

5 **N Harris & M O Hawksford**, *The Distributed-Mode Loudspeaker as a Broad-Band Acoustic Radiator*, 103rd Audio Engineering Convention, September 1997, preprint # 4526.

6 **B B Bauer**, *Equivalent Circuit Analysis of Mechano-Acoustic Structures*, Journal of the Audio Engineering Society, Vol. 24, No.8, pp 643-655.

7 **M. Tashiro, G. Bank & M. Roberts;** *A New Flat Panel Loudspeaker for Portable Multimedia*, 103rd Audio Engineering Convention, September 1997, preprint # 4527.

8 **AkAbak**, *Panzer & Partner*, Steinstrasse 15, D-81667, Munich, Germany.

9 **H Azima & N Harris**, *Boundary Interaction of Diffuse Field Distributed-Mode Radiators*, 103rd Audio Engineering Convention, September 1997, preprint # 4635.

10 **M Colloms & C Ellis**, *Diffuse field planar loudspeakers in multimedia and Home Theatre*, 103rd Audio Engineering Convention, September 1997, preprint # 4545.