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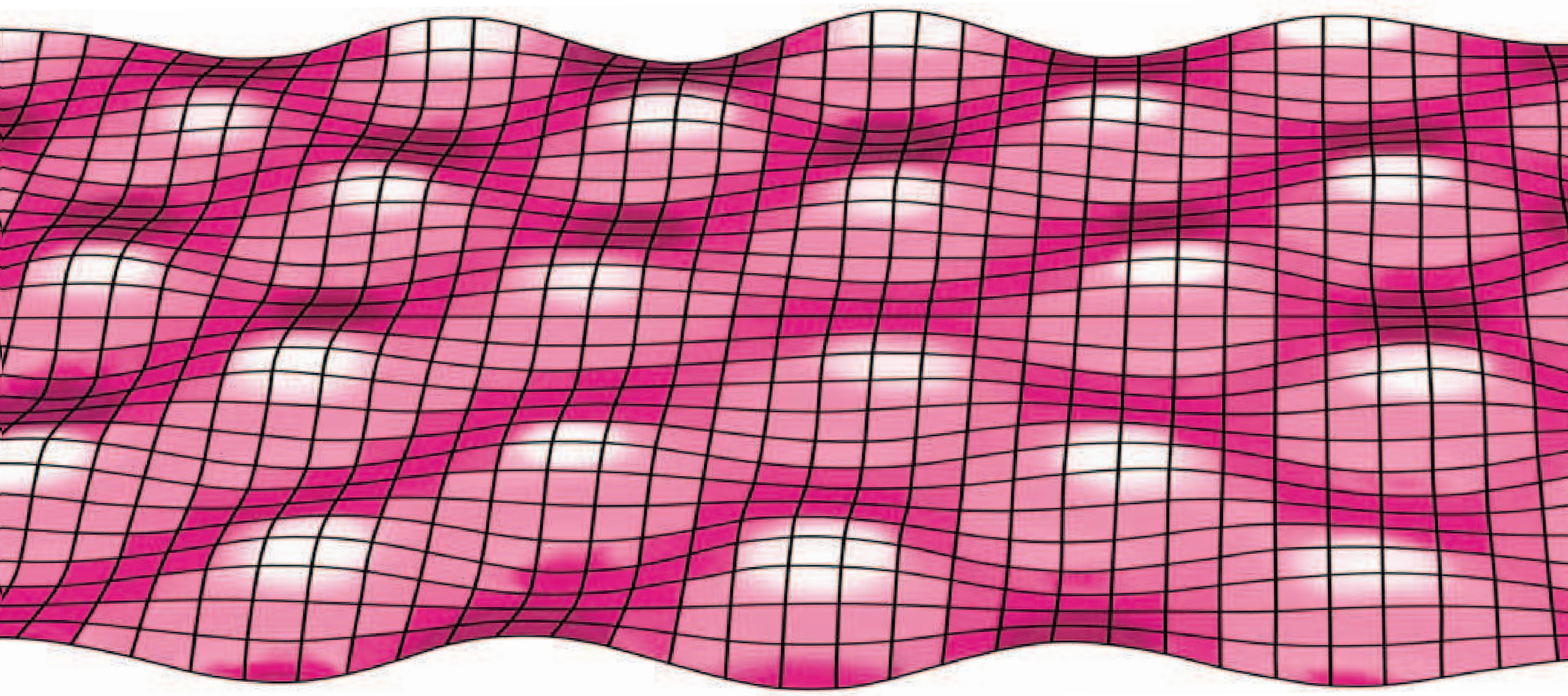


01 introduction

NXT has developed a radically different loudspeaker technology that offers significant acoustic advantages over conventional alternatives and opens up exciting new design potentials. The object of this technology review is to introduce NXT's technology, explain its numerous unique features and describe its particular advantages in the many applications to which it is being applied. The pace of development, particularly in respect of NXT's commercial exploitation, is rapid; this document represents the situation in January 2002.

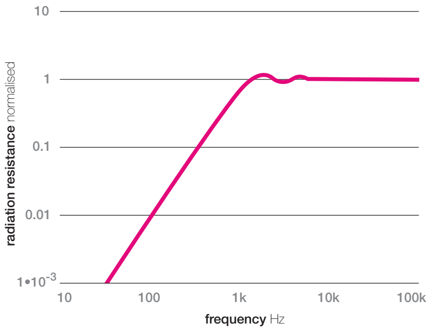
Much of the past 40-plus years of loudspeaker development has revolved around identifying, understanding and then suppressing diaphragm resonances and their resulting coloration and 'smear'. What we will describe here is an entirely different approach which rather than attempting to eliminate diaphragm resonance encourages and exploits it. In so doing, NXT's SurfaceSound and SoundVu technologies effectively tear up the loudspeaker rulebook as we have known it.

Audio professionals are understandably wary of an idea that so comprehensively inverts the conventional wisdom. But if you read through this description of our technology we are confident you will understand why we at NXT believe this innovation actually brings major benefits to both loudspeaker users and loudspeaker designers.

The first question to address is: why should we need a new loudspeaker paradigm when so much academic and design effort has been expended on perfecting current technology? To answer that, we need to go back to the basic principles of how conventional loudspeakers operate and identify the fundamental restrictions on performance that they impose.

Conventional loudspeakers, whatever method of transduction they use (electromagnetic, electrostatic, piezoelectric, etc), aim at achieving pistonic motion of the diaphragm, at least over the lower portion of the operating range. By pistonic we mean that the diaphragm moves as a rigid whole. In acoustic terms, such a loudspeaker is mass-controlled over most of its passband. For a given input voltage the motor generates a force that is constant with frequency, the diaphragm resists with a mass (its own moving mass plus that of the air load) and so, by Newton's second law of motion (F=ma), the acceleration of the diaphragm is constant with frequency. As a corollary, its displacement decreases with increasing frequency at a rate of 12dB per octave (*ie* it quarters with every doubling of frequency).

figure 1 radiation resistance vs frequency
for a 6-inch cone driver



At low frequencies, where the wavelength in air is large compared with the diaphragm dimensions, this is just what we want. The real part of the diaphragm's radiation resistance figure 1, into which the driver dissipates acoustic power, increases with frequency at exactly the same rate as the diaphragm's displacement decreases, with the result that acoustic power output is constant.

As frequency continues to rise, however, and the wavelength in air decreases to the point where it becomes comparable to the diaphragm dimensions, a major change occurs. Instead of continuing to rise, the real part of the radiation impedance reaches a limiting value and essentially becomes a constant for all higher frequencies.

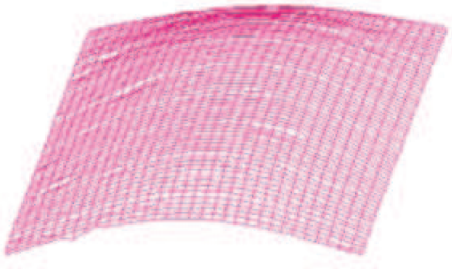
Consequently the diaphragm's acoustic power output now begins to fall at a rate of 12dB per octave. This doesn't mean that the on-axis pressure response drops off: what usually happens is that the diaphragm's acoustic output becomes restricted to progressively narrower solid angles. In other words, it becomes directional: it begins to beam.

Variation of directivity with frequency is one of the great bugbears of loudspeaker design. If we listened to reproduced sound in anechoic environments (and were prepared to sit within a closely confined listening area) it wouldn't matter: we would hear the diaphragm's on-axis output and nothing else. But conventional listening rooms are far from anechoic, so a loudspeaker's output off the listening axis has a significant effect on what we hear. Because of frequency-dependent directivity, the direct, reflected and reverberant sounds in a room all have different tonal balances. Even if a conventional loudspeaker were to have an absolutely flat on-axis response and were entirely free of resonance – a tall order – its varying off-axis response would still colour the sound and introduce imaging aberrations.

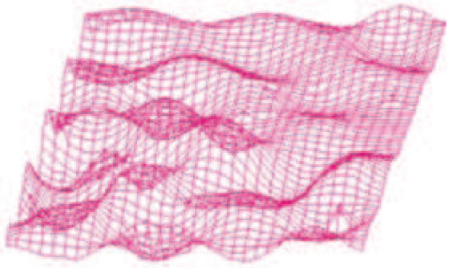
An obvious solution would be to use a small enough diaphragm to force the 'knee' in the radiation resistance curve above the audible frequency range. But such a diaphragm would have to undergo enormous, impractical excursions to produce the volume displacements necessary at low frequencies. So loudspeaker designers are typically forced to compromise and deploy multiple drive units of progressively decreasing diaphragm size. Large diaphragms provide the volume displacement necessary to reproduce low frequencies; small diaphragms take over at higher frequencies before the output of the larger units becomes too directional. Even so the speaker's directivity still varies significantly with frequency, while the use of crossovers to divide up the frequency range brings with it a host of unwelcome side effects: phase distortion, further disruption of off-axis output, more reactive elements in the loudspeaker load and sound quality issues related to capacitor performance and the saturation behaviour of inductor cores.

A single drive unit covering the entire audible frequency range with constant directivity would banish these problems and, as a further important benefit, provide consistent sound over a much larger listening area. But, for the reasons outlined, this simply isn't achievable using conventional techniques. So we appear to have reached an impasse.

figure 2 modal behaviour of an NXT panel
at low



and mid frequencies



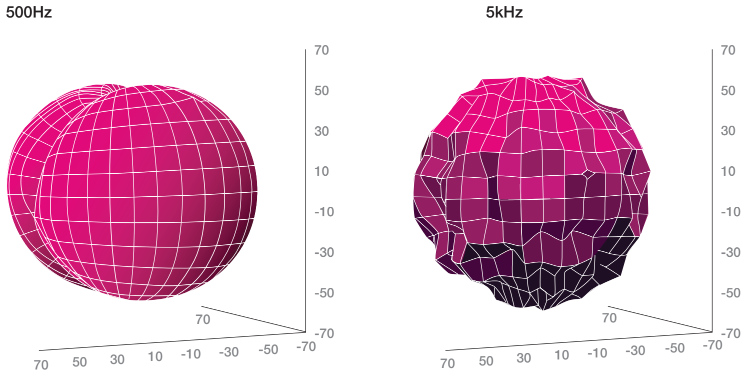
02 abandoning the piston

What if we abandon the concept of pistonic motion and consider instead a diaphragm vibrating randomly across its surface rather than coherently? Each small area of the panel vibrates, in effect, independently of its neighbours rather than in the fixed, coordinated fashion of a pistonic diaphragm. Think of it as an array of very small drivers, all radiating different, uncorrelated signals that nonetheless sum to produce the desired output.

Such a randomly vibrating diaphragm behaves quite differently because power is delivered to the mechanical resistance of the panel, which is constant with frequency. The radiation resistance is now insignificant. As a result, diaphragm dimensions no longer control directivity: you can make the radiating area as large as you wish without high frequency output becoming confined to a narrow solid angle about the forward axis. Such diaphragm behaviour clearly opens up the possibility of a full-range driver freed from the familiar restraints and compromises.

Nice trick if you can do it, but how can you make a diaphragm vibrate randomly? Actually you can't, but you can get very close to it by using what we term distributed-mode (DM) operation, on which NXT loudspeakers are based. Essentially this involves designing a diaphragm/excitation system in which a large number of modes are excited evenly in both frequency and amplitude. The resulting vibration is so complex that it approximates random motion figure 2. This is enough to free the speaker from the directivity-related problems described above, as is apparent from the three-dimensional polar diagrams of figure 3. (For a more detailed description of how NXT panels radiate, see the boxed text entitled Distributed-Mode Operation on page 25.)

figure 3 an NXT panel's quasi-random vibration
ensures wide directivity that is substantially independent of frequency



500Hz **5kHz**

Although an NXT panel's vibrational behaviour appears random, the process of designing it is deterministic. Provided you know a few key parameters – the size and shape of the panel (it can be curved in one or more planes), the position of the exciters (the driving elements) and the bending stiffness, surface density and internal damping of the panel material – it is possible to predict the acoustic performance with a high degree of accuracy. Loudspeaker designers habituated to the inherent unpredictability of conventional drive unit design find this aspect of the technology particularly exciting.

But the panel itself operates wholly in resonance, a feature of distributed-mode loudspeakers (DMLs) that worries audio enthusiasts and engineers who have been conditioned to regard resonance as anathema. Doesn't all this resonance in the panel colour the sound unacceptably? The surprising answer is no, it doesn't, because of the highly complex nature of the panel's vibration. An NXT panel's impulse response figure 4 displays a long resonant 'tail' which would damn any conventional loudspeaker, but its sound is clear and transparent, in keeping with the flat measured power response figure 5.

figure 4 typical impulse response
of an NXT panel

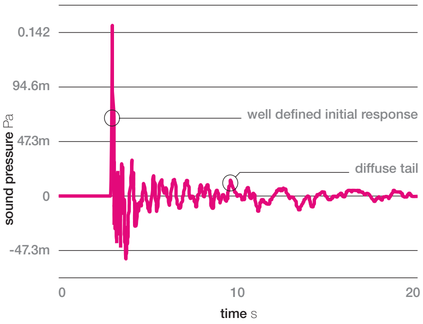
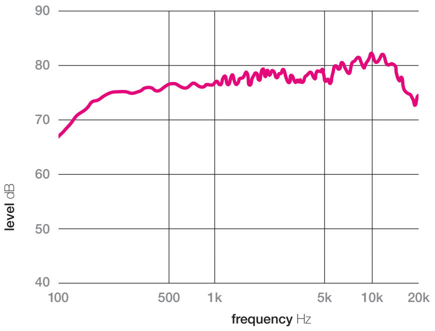


figure 5 optimal placement of the exciter
and control of panel bending modes results in a smooth and near-flat power response



For those who have the notion that a DML, being a modal object, would only work well in the higher frequency range, psychoacoustic research has shown that, in well designed DMLs where modal distribution has been optimised, above 2 to 2.5 times the fundamental bending frequency of the panel, perceived sound is indistinguishable from a perfect non-modal source. For example, an A4-size DML may have a fundamental mode at 100Hz and in practice be usable from 200-250Hz upwards. Whereas most conventional loudspeakers are forced to cross over between a woofer and tweeter in the ear's most sensitive region around 3kHz, an NXT panel – if it needs supplementing at all – only requires a conventional woofer to cover the lowest octaves of the audible frequency range. This makes a seamless transition much easier to achieve.

With respect to distortion, NXT panels typically perform as well or better than conventional alternatives figures 6 and 7. This is because, in the frequency range of interest, panel vibrations are very small in amplitude (which puts much reduced demand on the coil excursion of the exciter) and fall well within the panel's linear elastic range.

In summary, it is true to say that the design goals for a conventional loudspeaker have to be a compromise. You are trying to deliver acoustical output across a wide bandwidth, yet when the radiated wavelength becomes smaller than the diaphragm circumference, the loudspeaker's power output begins to fall. Because of this, and the need to provide sufficient volume velocity to reproduce frequencies at the lower extreme of its passband, a conventional driver's power bandwidth is typically limited to between four and five octaves. This remains a physical limitation of pistonic speakers even if we could design and make a perfect pistonic radiator. Consequently, conventional driver design always embodies trade-offs between bandwidth, directivity and smoothness of frequency response. In the finest conventional loudspeakers these engineering compromises are skilfully struck, but they remain compromises.

figure 6a distortion versus frequency
for a 500x700mm public address SurfaceSound panel at 1W input power

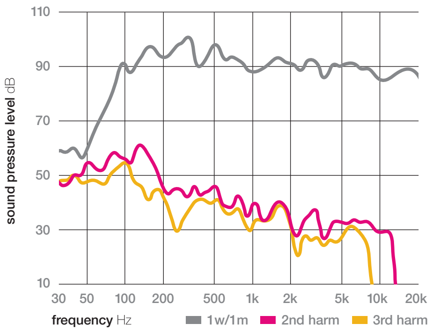


figure 6b distortion versus frequency
for a 500x700mm public address SurfaceSound panel at 10W input power

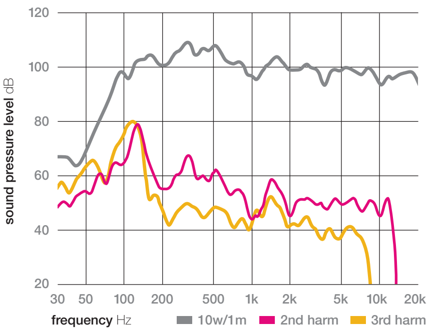


figure 7a distortion versus SPL for a 500x700mm public address SurfaceSound panel 150Hz-20kHz

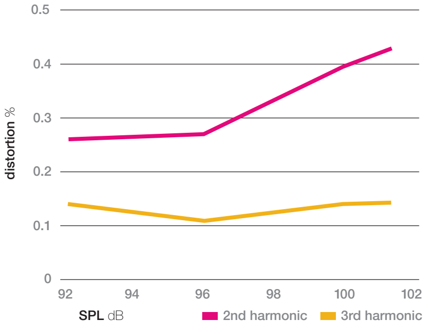
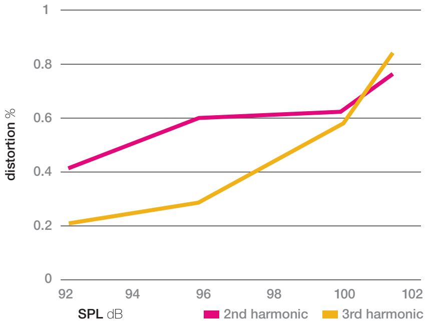


figure 7b distortion versus SPL for a 500x700mm public address SurfaceSound panel 100Hz-20kHz



NXT panels represent a distinct alternative. The modal behaviour of the panel makes its output diffuse, and optimising panel mode structure ensures a broad passband of greater than eight octaves. As we refine panel materials, exciter locations, boundary conditions and so forth, we approach the behaviour of a randomly vibrating panel whose power output is largely independent of size. Separating output directivity from the panel dimensions releases us from the traditional compromises loudspeaker designers have faced for more than 70 years. Smooth, dense modal behaviour confers predictable, deterministic, scalable acoustic behaviour that, until now, has been an unfulfilled dream.

03 **acoustic properties**

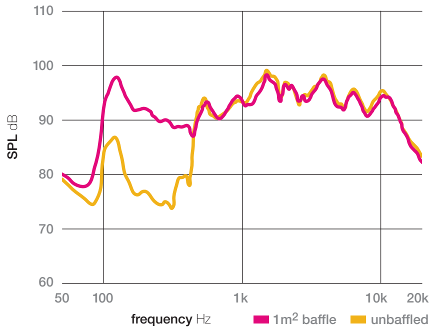
One of the most significant properties of NXT panels is that they are uniquely scalable. Because they maintain the same, wide dispersion characteristics irrespective of their dimensions they can be applied across the gamut of loudspeaker sizes, from small panels on mobile phones right up to large-area projection screens. In each case uniform dispersion is maintained, providing consistent sound intensity and frequency balance over a much wider listening 'window' than pistonic drive units can provide, even when arranged in complex arrays.

Depending on the panel size and amount of mechanical damping, coincidence effects in a bending panel (which occur above the frequency at which wave speed in the panel equals the speed of sound in air) can produce a range of acoustic effects which may or may not be desirable. One acoustic consequence of coincidence is the over-prominence of off-axis power in a given frequency range. This effect may be exploited in applications where negative directivity is an advantage (such as ceiling speakers). However, in most cases we do not wish to exploit coincidence and therefore through various design techniques this effect is either reduced to negligible levels or designed to occur outside the audio band.

In contrast to conventional loudspeakers, the performance of NXT panels actually improves as panel size is increased because the frequency of the fundamental bending resonance is lowered. This not only has the benefit of extending the bass response but also increases modal density in the low and mid frequencies.

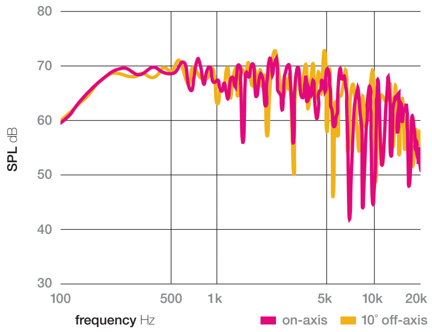
With an optimised panel design the bandwidth is typically eight octaves (*cf* approximately 10 octaves for the entire audible frequency range). With smaller open-back panels in particular, the addition of a baffle – which moves partial cancellation of the forward and rearward output to lower frequencies – is a practicable method of increasing bass output figure 8.

figure 8 baffling can be used to increase a panel's low frequency output (500 cm^2 panel)



Because of the modal nature of the panel's behaviour, single-point, high-resolution measurements of sound pressure versus frequency generally display a frequency response quite different from that expected with pistonic operation figure 9. A slight movement of the measurement microphone will produce a different response, albeit with the same overall trend. Fortunately, this type of measurement does not accurately reflect how the panel output is perceived. A much more relevant measurement is of the panel's acoustic power output versus frequency, which is determined by combining the pressure responses measured across a grid of microphone positions, or in a reverberant chamber. The power response is much smoother and better represents the perceived frequency balance of the panel's output figure 5.

figure 9 single-point sound pressure measurements display fine structure that is strongly dependent on the positioning of the microphone



Another unusual characteristic of NXT panels is that in applications where the back of the panel is not required to be enclosed, as in free-standing loudspeakers, the power radiated from the back face sums constructively with the power radiated from the front. This occurs because of the complexity of distributed-mode radiation and the uncorrelated phase of the individual radiating elements as seen from the far field. (We use the term 'diffuse dipole' to describe this acoustic radiation behaviour.)

figure 10 finite element analysis of the interaction of a piston speaker with a single room boundary

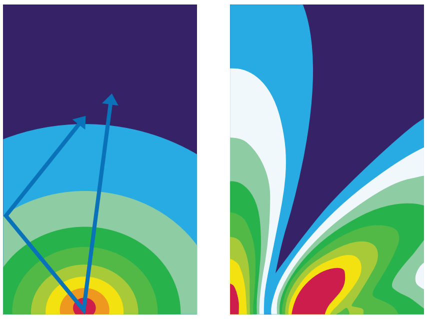


figure 11 finite element analysis of the interaction of an NXT panel with a single room boundary

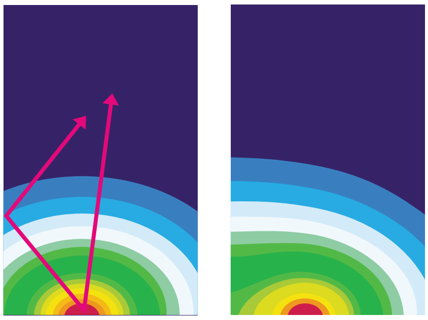
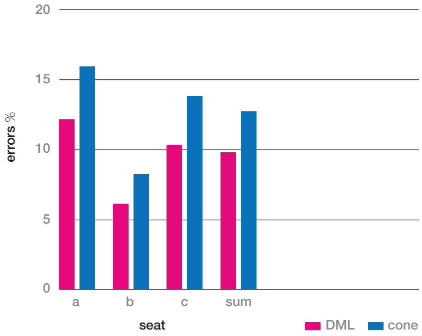


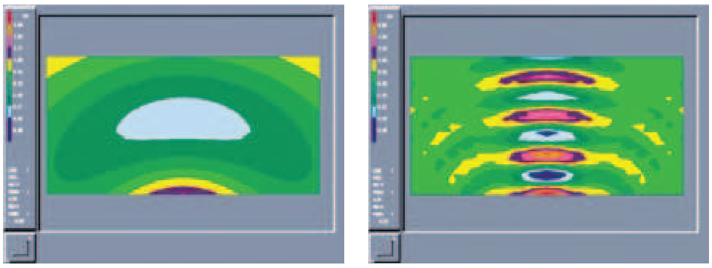
figure 13 virtual image location
in a two-channel stereo system is more accurate with distributed-mode sound sources



Because their diffuse acoustic radiation reduces destructive interaction with nearby reflective surfaces, free-standing NXT panels have no requirement for an enclosure. This eliminates the problems associated with loudspeaker cabinets, which have their own spurious resonances, colorations and cost penalties.

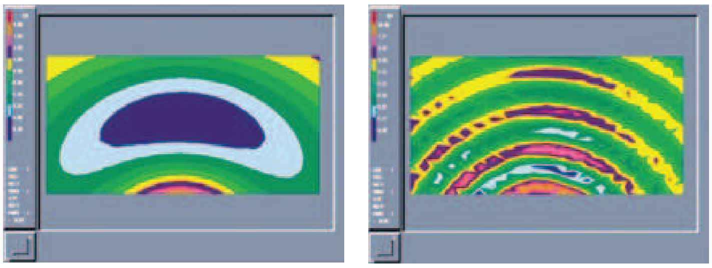
Anyone familiar with the sound of conventional omnidirectional or near-omnidirectional loudspeakers might expect NXT panels to produce a relatively imprecise, smeared stereo image. But in typical domestic surroundings the imaging is at least as well defined and stable as with conventional directional loudspeakers listened to from the stereo 'sweet spot', despite the panels' broad radiation pattern. This is because their diffusivity reduces the detrimental effect of interactions with room boundaries figures 10 and 11. Outside the typically small area of optimum stereo, we have found that NXT panels actually deliver superior imaging because of their better off-axis performance and reduced room interaction. Another important contributing factor is the way NXT panels, quite counter-intuitively, behave like a point source in the far field figure 12. Research work quantifying stereo localisation errors has shown that listeners can more reliably localise virtual sound sources with DMLs than they can with conventional loudspeakers figure 13.

figure 12 finite element simulation of same radiating area cone versus a DML
shows how the DML approximates a point source at higher frequencies while the cone beams



piston 500Hz

piston 4000Hz

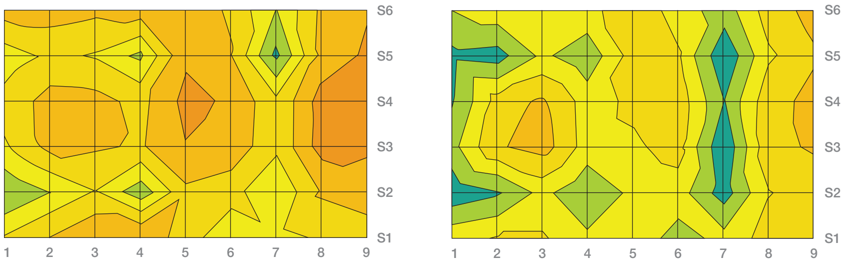


dml 500Hz

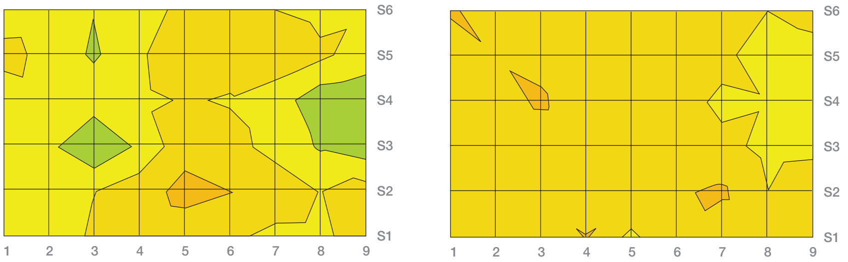
dml 4000Hz

figure 14 sound pressure contours here measured in a car cabin, show that NXT panels (right-hand plot at both frequencies) maintain more consistent sound pressure level throughout an enclosed listening space

piston 330Hz **DML** 330Hz



piston 1.8kHz **DML** 1.8kHz



With conventional wide-dispersion loudspeakers you also tend to hear much more contribution from the listening room. Standing-wave resonances are more pronounced, so the tonal balance varies significantly as you change listening position, and interaction with room boundaries is worsened too, making speaker placement more critical. NXT panels behave quite differently as a result of the diffuse nature of their radiation. Because their sound does not emanate from a fixed, well-defined point in space the distribution of sound pressure within the listening space is actually much more even with an NXT panel than with a conventional loudspeaker figure 14. So room interaction is actually reduced figure 15.

NXT has developed a means of quantifying the diffuse nature of DML radiation called spatial correlation. This involves measuring the panel's acoustic output on and off the forward axis and cross-correlating the two signals to generate a correlation coefficient. A correlation coefficient of 1 indicates that the two signals are identical, whereas a correlation coefficient of 0 indicates that they are entirely uncorrelated. If the correlation coefficient is measured across a range of angles off-axis, a polar spatial correlation plot like figure 16 can be generated illustrating how the correlation between on- and off-axis output changes around the loudspeaker.

The blue plot in figure 16 shows the spatial correlation of a typical cone loudspeaker. Even at large angles away from the reference axis the correlation coefficient remains high. This means that sound reflected from a room's floor, side walls and ceiling will interact strongly with the direct output from the loudspeaker. Contrast this with the red plot which shows a typical spatial correlation result for a distributed-mode loudspeaker.

figure 15 spectrograms of sound pressure level (false colour) versus frequency and distance confirm that an NXT panel interacts less destructively with a single boundary

conventional **NXT**

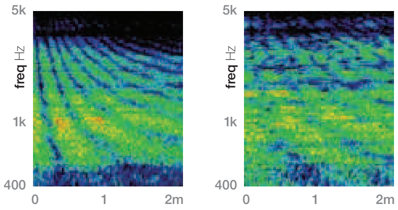


figure 16 spatial correlation polar plots for an NXT panel and cone speaker illustrate the unique diffuse nature of the panel's sound radiation

▬ **panel speaker** correlation falls off with angle
▬ **cone speaker** fully correlated sound field

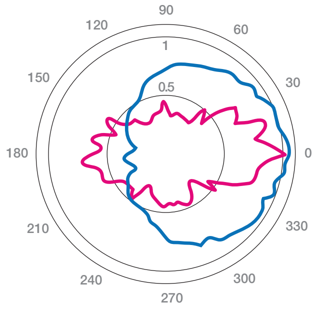
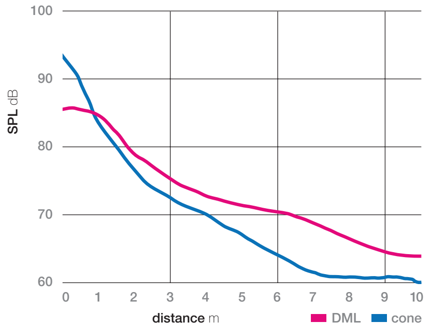


figure 17 broadband comparison of sound pressure level versus distance shows that the output of an NXT panel is significantly better maintained than that of a cone alternative – normalised at 1m from source



Because of the diffuse nature of a DML's acoustic output the correlation coefficient is much reduced off the reference axis, so room interaction is quelled.

Another desirable consequence of diffuse radiation together with wide directivity is that in a given room the acoustic output, and hence loudness, of an NXT panel falls away more slowly with increasing speaker-listener distance than is the case with a diaphragm vibrating coherently. The sound pressure from a conventional loudspeaker approximately obeys the inverse square law, falling by 6dB for each doubling of distance. With a DML the fall-off with distance is reduced, while the uniformity of sound distribution is increased figure 17.

These three factors – the NXT panel's wide directivity, its reduced destructive interaction with room boundaries and its better maintained loudness with increasing distance – combine to make the sound coverage within a room unusually even. Whereas the loudness of a conventional, pistonic loudspeaker falls away quite rapidly as you move off-axis or further away, with an NXT panel the loudness is significantly better maintained figure 18.

figure 18 3D contour plots of loudness versus room position confirm that an NXT panel (left) maintains more even loudness across a wide range of listening positions

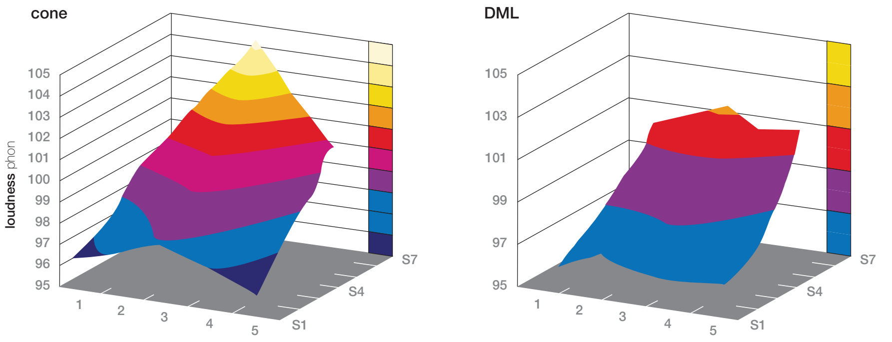
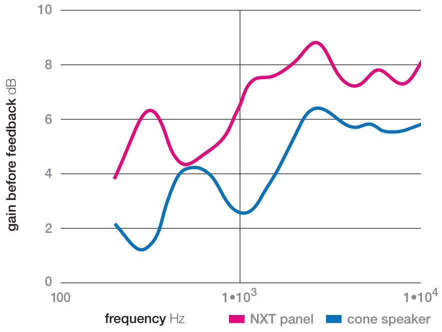


figure 19 The diffuse radiation of an NXT panel improves acoustic feedback margin where speakers and microphones are in close proximity



In public address and sound reinforcement systems directional loudspeakers are often employed to enhance intelligibility by reducing reflected sound energy, and (where loudspeakers and microphones are in close proximity) to suppress acoustic feedback ('howlround'). The wide directivity of NXT panels might appear to disqualify them from these applications, but once again the diffuse nature of a DML's radiation confounds expectations based on conventional wisdom. In practice it is found that the low off-axis spatial correlation of NXT panels acts to improve intelligibility. Susceptibility to acoustic feedback is also reduced, increasing the gain margin before regeneration occurs figure 19.

The diffuse nature of NXT panels' radiation also provides the required rear channel diffusion in home theatre applications and makes the addition of a centre channel a very effective means of improving 'centre fill' in car audio installations.