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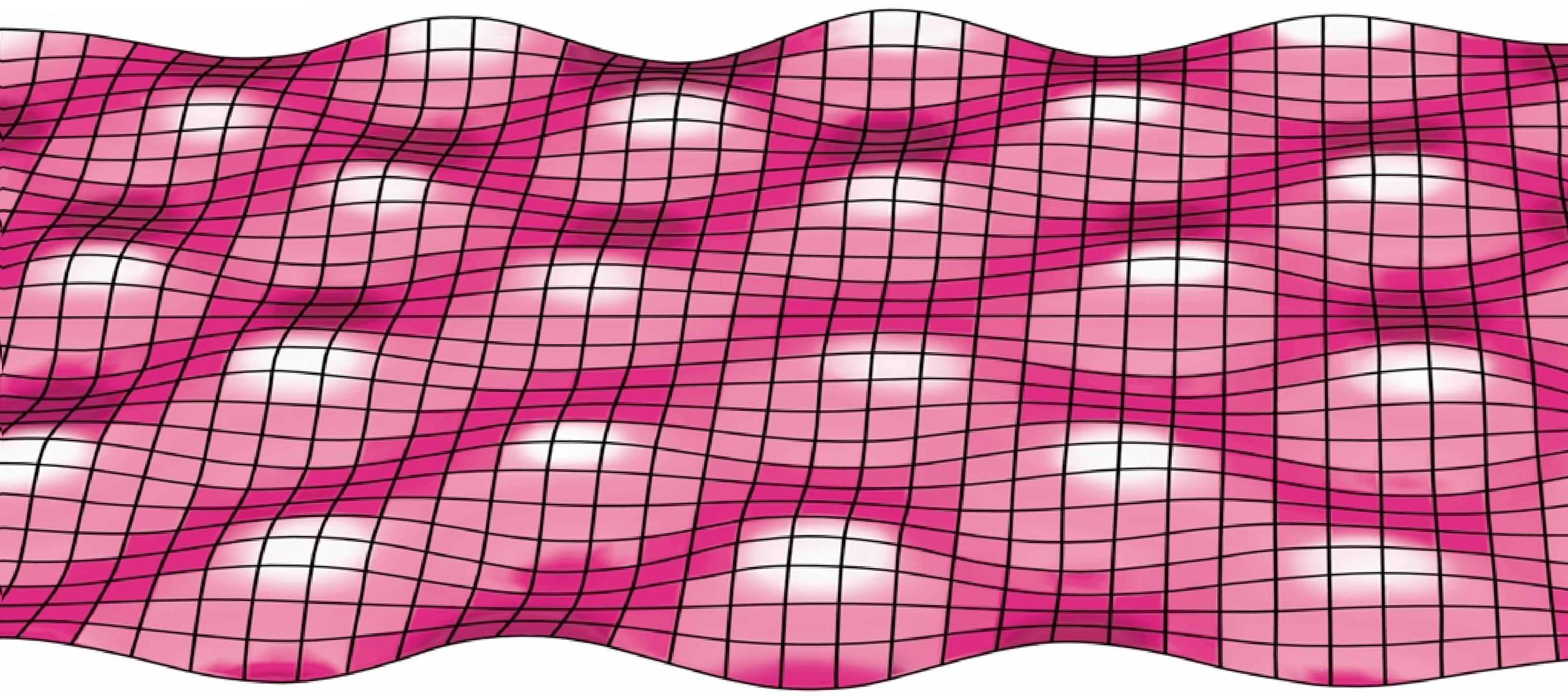


01 introduction

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.

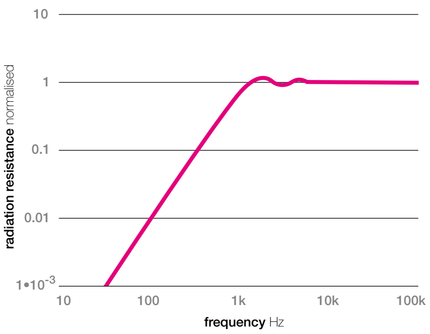
Much of the past 40-plus years of loudspeaker development has revolved around identifying, understanding and then suppressing diaphragm resonances and their resulting coloration and 'smear'. What we will describe here is an entirely different approach which rather than attempting to eliminate diaphragm 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.

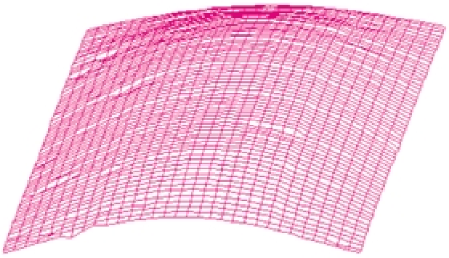
Consequently the diaphragm's acoustic power output now begins to fall at a rate of 12dB per octave. This doesn't mean that the on-axis pressure response drops off: what usually happens is that the diaphragm's acoustic output becomes restricted to progressively narrower solid angles. In other words, it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

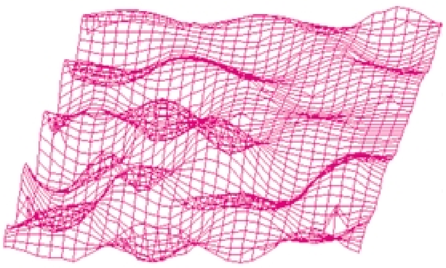
An obvious solution would be to use a small enough diaphragm to force the 'knee' in the radiation resistance curve above the audible frequency range. But such a diaphragm would have to undergo enormous, impractical excursions to produce the volume displacements necessary at low frequencies. So loudspeaker 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



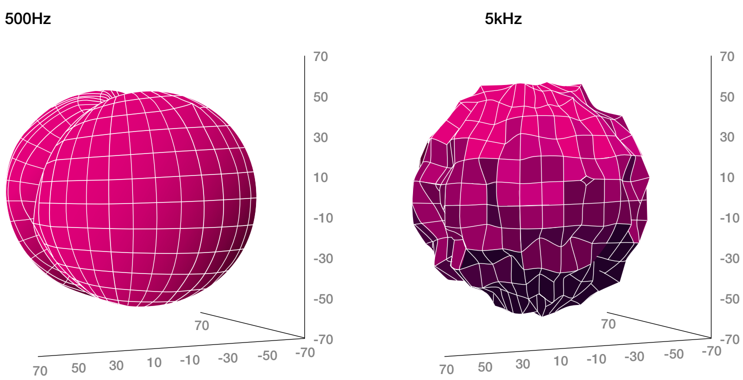
02 abandoning the piston

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



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

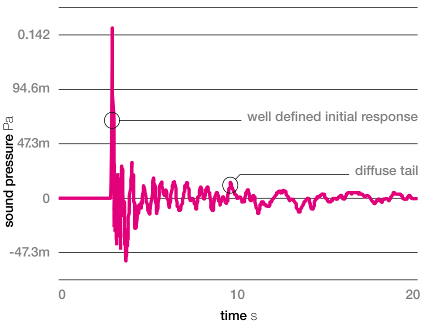
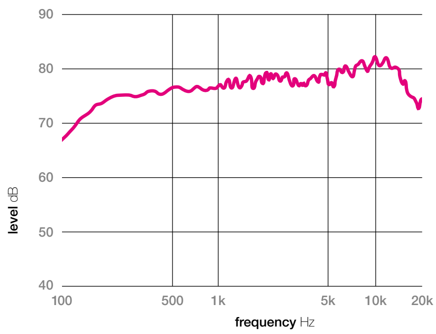


figure 5 optimal placement of the exciter
and control of panel bending modes results in a smooth and near-flat power response



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

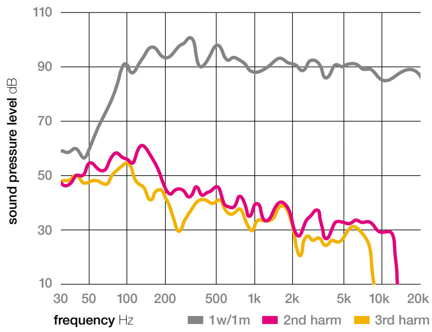


figure 6b distortion versus frequency
for a 500x700mm public address SurfaceSound panel at 10W input power

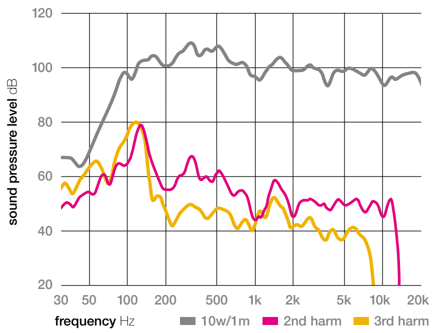


figure 7a distortion versus SPL for a 500x700mm public address SurfaceSound panel 150Hz-20kHz

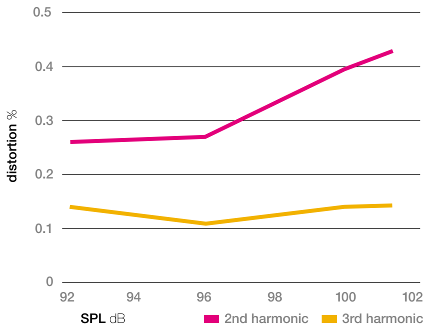
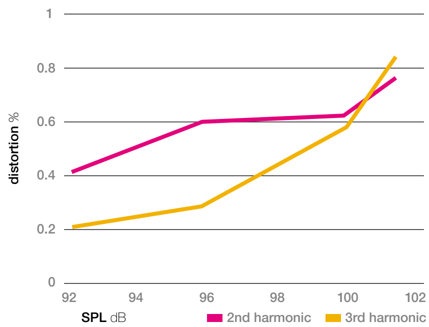


figure 7b distortion versus SPL for a 500x700mm public address SurfaceSound panel 100Hz-20kHz



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.

figure 8 baffling can be used to increase a panel's low frequency output (500 cm² panel)

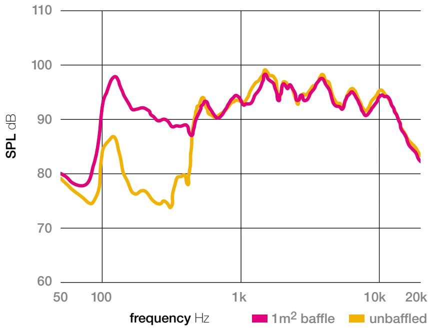
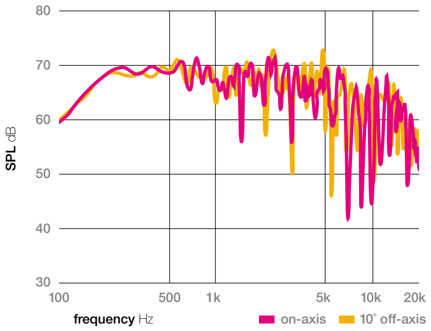


figure 9 single-point sound pressure measurements display fine structure that is strongly dependent on the positioning of the microphone



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.

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.

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

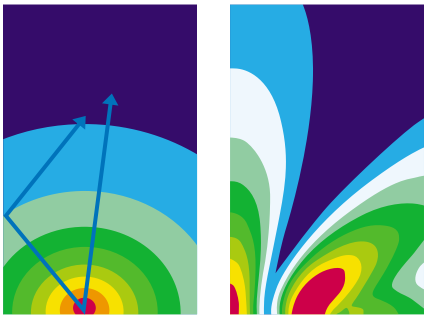


figure 11 finite element analysis of the interaction of an NXT panel with a single room boundary

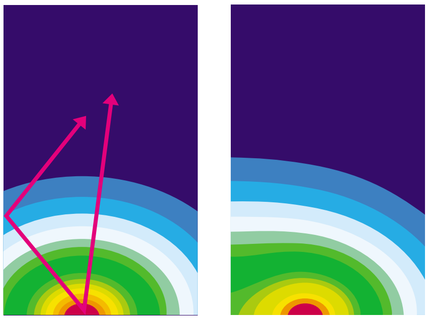
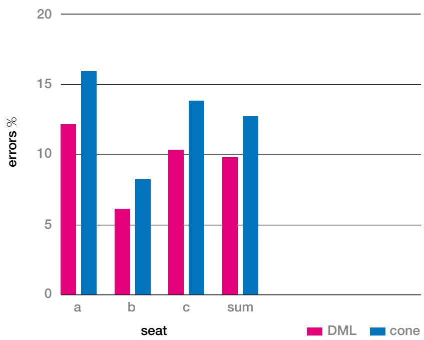


figure 13 virtual image location
in a two-channel stereo system is more accurate with distributed-mode sound sources



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

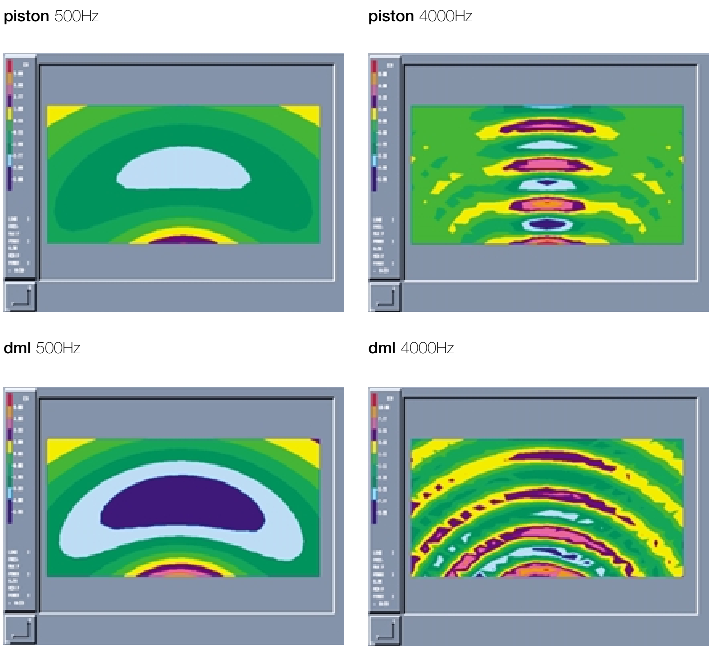


figure 14 sound pressure contours here measured in a car cabin, show that NXT panels (right-hand plot at both frequencies) maintain more consistent sound pressure level throughout an enclosed listening space

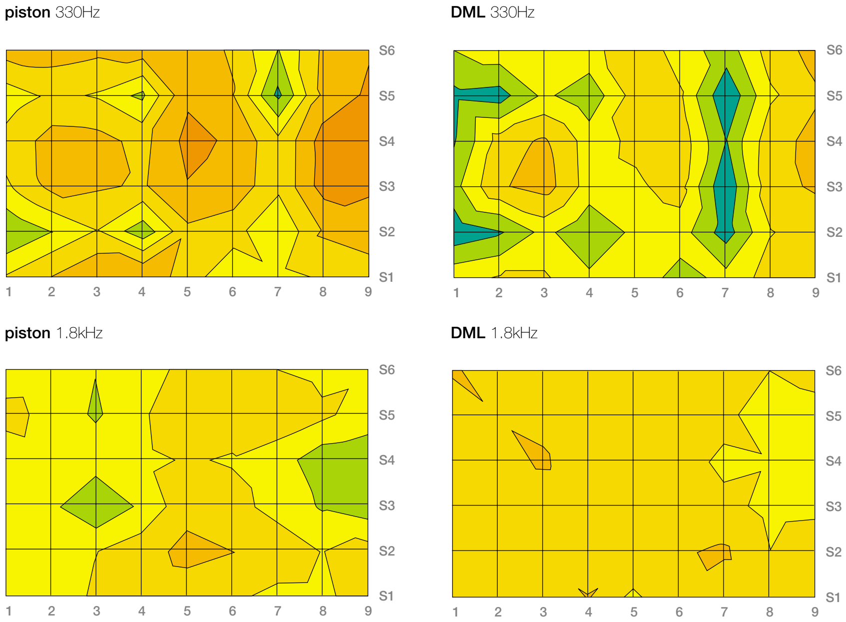


figure 15 spectrograms of sound pressure level (false colour) versus frequency and distance confirm that an NXT panel interacts less destructively with a single boundary

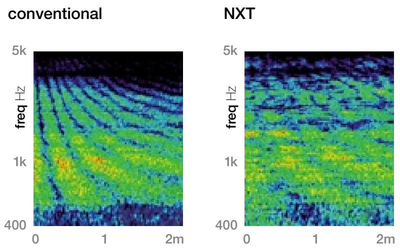
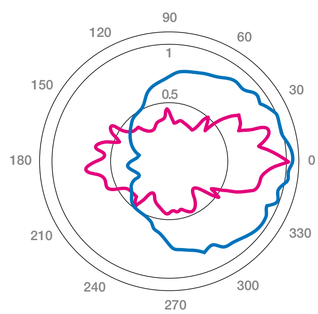


figure 16 spatial correlation polar plots for an NXT panel and cone speaker illustrate the unique diffuse nature of the panel's sound radiation

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

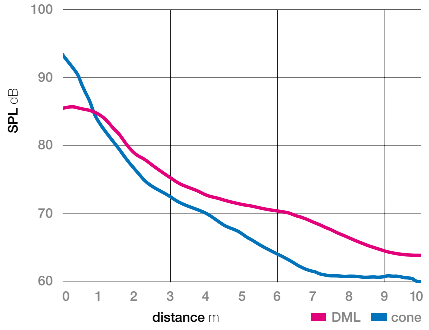


With conventional wide-dispersion loudspeakers you also tend to hear much more contribution from the listening room. Standing-wave resonances are more pronounced, so the tonal balance varies significantly as you change listening position, and interaction with room boundaries is worsened too, making speaker 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 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

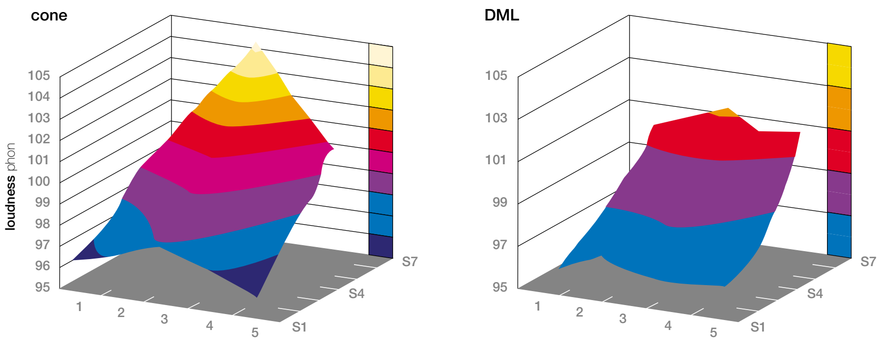
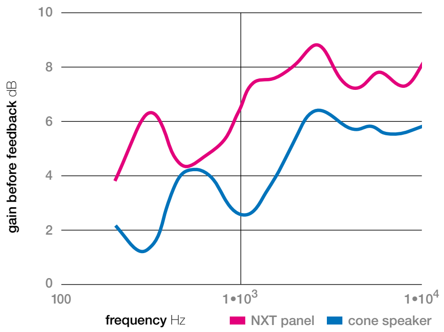


figure 19 The diffuse radiation of an NXT panel improves acoustic feedback margin where speakers and microphones are in close proximity



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.

04 SoundVu technology

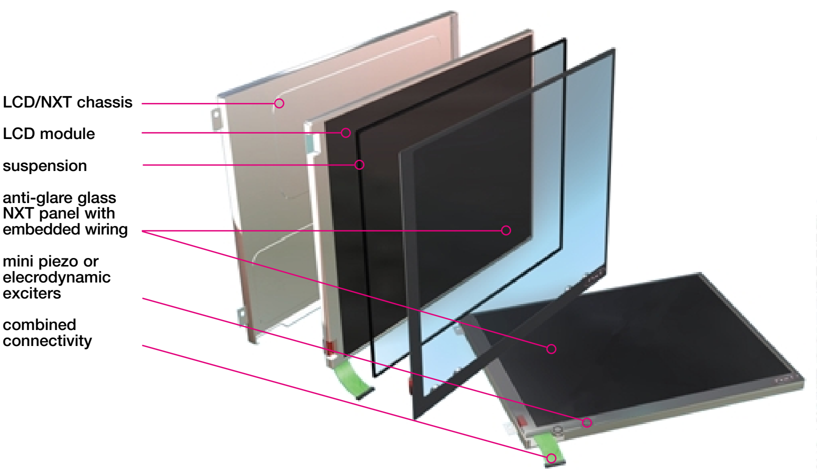
The feature that distinguishes NXT's two DML technologies – SoundVu and SurfaceSound – is that SoundVu technology is conceived to be used with visual displays, thereby allowing them to double as loudspeakers. While the operating principle of SoundVu technology and its acoustic characteristics are similar to those of SurfaceSound technology, the imposed constraint of complete panel transparency demands distinct technical solutions.

Like SurfaceSound panels, SoundVu panels can span a wide range of sizes, from the compact displays of mobile phones and PDAs right up to the large display area of a top-specification widescreen television. In all instances the NXT panel comprises an additional transparent sheet, of an optical polymer material or glass, positioned immediately in front of the display screen and separated from it by a small air gap figure 20. This gap varies in depth, according to the size of the panel, up to a maximum of a few millimetres. Although the addition of a SoundVu panel adds to reflection losses as a result of the two further air/screen interfaces it introduces, with modern high-performance anti-reflection films and coatings these can be reduced to a minimum without significant cost penalty. Parts consolidation can be achieved by having the SoundVu panel function as an electromagnetic interference (EMI) and anti-glare screen.

Perceptible screen shimmer is avoided by preventing frequencies below about 200Hz from entering the panel and, if required, reproducing them via a subwoofer. In this respect SoundVu technology is no different to some SurfaceSound applications where a subwoofer is used to extend low frequency output.

The advantages that accrue from using SoundVu technology in preference to separate loudspeakers are considerable. From the design viewpoint, a SoundVu panel is the nearest one can get to a zero footprint loudspeaker. All it may add are a few millimetres to a display's depth, and not even that if it replaces the EMI screen already incorporated into many displays, so it is particularly well suited to ultra-thin plasma and LCD screens.

figure 20 exploded diagram of a typical SoundVu module



The usual acoustic advantages of distributed-mode operation – wide coverage, better maintained loudness and reduced room interaction – are also supplemented in this instance by the intimate 'locking' of the sound and image, which now originate from the same point in space. Particularly with on-screen dialogue, this avoids the disconcerting uncoupling of sound and picture that often occurs even when loudspeaker units are positioned as closely as possible to the screen.

Although SoundVu technology uses a single DM panel it can be used, as a SurfaceSound panel can, to reproduce more than one channel. A psychoacoustic phenomenon called the precedence (or Haas) effect ensures that we localise a sound source principally from the 'first arrival' sound. This means that if exciters on either side of the panel carry separate channels, those channels appear to originate from separate positions. In principle, this allows a SoundVu (or SurfaceSound) installation to reproduce left, right and centre channels from a single panel.

Because of the need to integrate a SoundVu panel with the display itself, the two have to be designed as a complete package. For this reason NXT is working closely with both display, screen and end-product manufacturers to ensure that the integration is optimised in respect of both visual and sonic performance.

05 panel materials

A wide variety of materials are suitable for use as NXT SurfaceSound panels, ranging from low cost cardboard and plastic materials to hi-tech sandwich constructions using glassfibre or carbon fibre composite skins on honeycomb or expanded foam cores. Some are extant materials, already manufactured for other purposes (eg packaging), while others have been purpose designed for this application.

Over 200 panel materials have had their relevant physical properties quantified as part of NXT's component characterisation programme, and their parameters entered in the database of our PanSys design software (see page 20). Sandwich panels can be constructed using either static or continuous lamination processes figure 21a/b.

figure 21a sandwich construction panel materials
can be manufactured using static press moulding

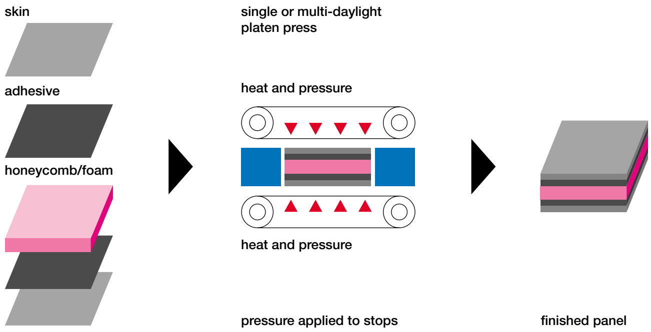


figure 21b or using continuous lamination techniques

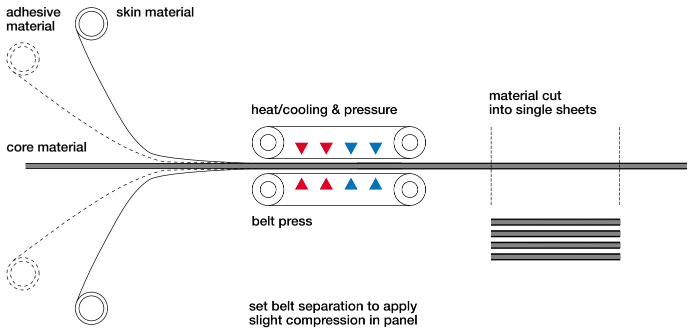
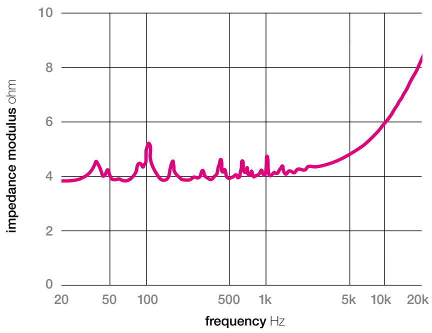


figure 22 typical modulus of impedance trace for an NXT panel shows a benign, largely resistive load that is easy to drive



06 exciters

A variety of exciter technologies are appropriate for energising an NXT panel, including piezoelectric transducers, but in most applications the preferred option is a moving coil motor. This confers three principal advantages. First, it ensures compatibility with conventional amplifiers. In fact, NXT panels with moving coil exciters present notably benign amplifier loads, being essentially resistive at low and middle frequencies figure 22. As frequency rises the inductance of the voice coil becomes significant, the modulus of impedance increases and the load becomes reactive. But nowhere is there low modulus and large phase angle in combination, as there can be with other forms of loudspeaker. Second, it permits use of the existing manufacturing base. Third, it enables exploitation of the full bandwidth potential of an NXT panel.

Exciters – whether moving coil or otherwise – can be operated in two ways. In conventional moving coil loudspeakers it is usual for the motor unit to be realised with the magnet as a stator, clamped within the drive unit chassis, and the voice coil as the moving element, attached to the diaphragm. There is no direct equivalent for NXT panels. If it is required to clamp the magnet assembly – which can be advantageous in circumstances where high power handling is required, since heat can be transferred from the magnet assembly to a heatsink – a grounded magnet exciter can be used, in which the magnet is rigidly attached to the panel's frame. This can be finned, if necessary, to improve heat dissipation.

An alternative means of operation, which in many applications is preferable, uses an inertial exciter which requires no mechanical 'ground' reference. Here only the voice coil is attached to the panel, with the magnet assembly freely suspended. In this case the panel is energised by the reaction force that results from movements of the magnet.

Although moving coil exciters suffice in most applications, in the case of small SoundVu panels – for use in mobile phones and PDAs – there is clearly a need for something smaller and more efficient (to maximise battery life). To meet this requirement, NXT has developed a new concept in piezoelectric exciters called the DMA – distributed-mode actuator – which is described in greater detail on page 22.

07 value proposition – general

To summarise the acoustic advantages of NXT panels, they:

- are uniquely scalable.
- have a wide bandwidth (over eight octaves).
- offer wide directivity right across their passband.
- reduce undesirable interaction with the listening room.
- improve stereo imaging.
- maintain loudness better with distance.
- radiate sound additively from either face.
- remove the requirement for a crossover within the ear's most sensitive range.

In addition to these performance advantages, NXT panels also offer distinct practical benefits. In many applications, particularly where two conventional drive units and an attendant crossover network would be required to cover the same frequency range, an NXT panel offers potential cost savings and a reduction in complexity.

NXT panel loudspeakers, because they are so shallow even if an enclosure is required (to improve the consistency of performance when used in close proximity to a wall or other large reflective surface), also occupy less volume than conventional alternatives. This is a significant advantage in numerous circumstances. For instance, NXT-based PC multimedia speakers occupy less 'real estate' on the desktop, surround sound home theatre speaker installations are less visually and spatially intrusive, and space can be liberated in in-car installations to improve what car designers refer to as the vehicle's 'packaging'.

In the particular case of SoundVu technology, an NXT panel can have virtually zero footprint since the loudspeaker becomes an integral part of a visual display, typically adding only a few millimetres to its overall depth.

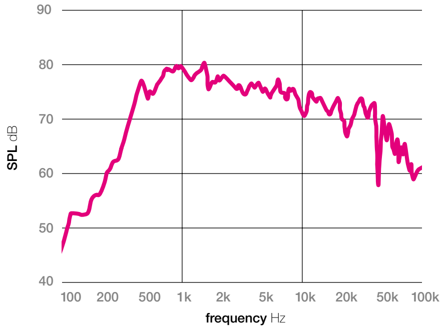
08 audio

The traditional image of the hi-fi enthusiast sitting in splendid isolation, listening to his system from the tiny stereo 'sweet spot', is increasingly untenable in a modern context. Both rooms and audio systems are expected to be more flexible, and listening to music or watching a movie is as likely to be a family activity as something enjoyed alone.

SurfaceSound panel speakers, whether used as part of a two-channel stereo system or within a multichannel surround sound set-up, offer the benefits of wider dispersion, more uniform loudness and reduced room interaction. These characteristics combine to guarantee a larger listening area, across which the sound maintains the tonal accuracy and believable virtual image previously associated with the stereo hot seat. In home theatre systems NXT panels have the additional advantage that the inherently diffuse nature of their sound radiation assures the required surround-channel diffusion, so that listeners are not conscious of the surround speakers as distinct entities.

The fact that these performance benefits are complemented by reduced loudspeaker footprint and increased flexibility of loudspeaker placement only adds to the attraction of NXT panels in circumstances where space is at a premium and there is a natural reluctance to clutter a multi-purpose domestic room with intrusive audio hardware.

figure 23 SurfaceSound supertweeter
uniquely combines a smooth, extended frequency response with wide directivity to ultrasonic frequencies



All this makes SurfaceSound technology particularly applicable to the general audio systems bought by non-specialist consumers, but that is not to say that NXT panels have less to offer the dedicated hi-fi enthusiast. The reduced interaction with room boundaries, improved stereo and lack of a crossover in the critical frequency range around 2-3kHz all mean that DM operation also brings tangible benefits to 'high-end' audio systems.

A major recent development within the audio and recording industries is the introduction of DVD-Audio and Super Audio CD. As well as providing multichannel capability, these new music carriers offer extended bandwidth potential above 20kHz (the effective upper frequency limit of CD). Although the significance of inaudible ultrasonic frequencies to accurate sound reproduction is a controversial issue, many recording engineers, hi-fi journalists and general audiophiles have reported improvements in sound quality when the frequency response of the source recording is extended in this way. Improvements are heard even when the loudspeakers have a falling response above 20kHz, however the effects are most obvious when the loudspeaker high frequency response is also extended, typically by the addition of an ultrasonic supertweeter.

A major weakness of a pistonic drive unit in this role is that the familiar 'beaming' of output at high treble frequencies becomes even more acute as the wavelength of the radiated sound reduces still further. At 20kHz the wavelength of sound in air is about 17mm, which is already much less than the circumference of a typical 25mm diameter dome tweeter. By 40kHz the wavelength has reduced to 8.5mm and the tweeter's acoustic output is even more tightly beamed. Realising the supertweeter as an NXT SurfaceSound panel overcomes this directivity problem, and additionally provides a much wider overall bandwidth. This allows a single small panel to fulfil the duties of both tweeter and supertweeter figure 23.

figure 24 Philips and TDK exploit SurfaceSound technology to realise multimedia speaker systems that are compact and stylish

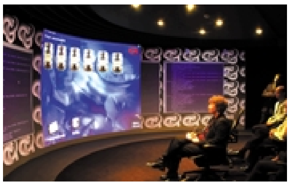
09 multimedia and computing

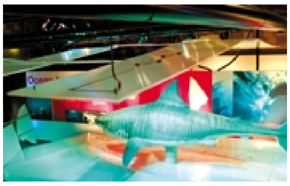
Audio is an increasingly important part of the computer experience, even for users who do not use their PC for gaming. Many people listen to CDs or watch DVDs at the computer, while sound clips form part of many programs and web sites and sometimes accompany emails.

The essential requirement in this application is to achieve a high quality of sound while occupying the minimum of valuable desktop space. SurfaceSound panels are ideal in this respect because they are so thin. Of course, their broad directivity also makes their positioning far less critical. This means that NXT multimedia speakers figure 24 can be placed in almost any convenient spot on the desktop or attached to a nearby wall or the sides of a monitor.

Cost savings and enhanced aesthetic opportunities complement these acoustic and practical advantages, conferring an impressive array of benefits.

figure 25 **two recent PA installations** that demonstrate the versatility of NXT panels
Immersive Virtual Reality Theatre, DTI, London (top) uses modular curved panels to create a 12 metre wide, 150-degree projection screen that provides intimate 'locking' of sound and image.
Predators exhibition, Natural History Museum, London has transparent panels to enhance the exhibits with surround sound





10 public address

In public address and sound reinforcement applications the prime requirement is for even audience coverage in respect of both spectral balance and loudness. Because of their wide sound dispersion, SurfaceSound panels meet these requirements 'out of the box' and are smaller, simpler, cheaper and more portable than conventional solutions using multiple drive arrays or constant directivity horns.

SurfaceSound panels are also uniquely flexible in fixed PA applications, as demonstrated by two installations in London – one at the Department of Trade and Industry and the other at the Natural History Museum figure 25. In the DTI Immersive Virtual Reality Theatre large SurfaceSound panels were assembled into a curved screen 12m wide and subtending an angle of 150 degrees, on to which images can be projected for interactive presentations. Because the screen also functions as the loudspeaker, audio and picture are intimately associated in a way not possible with conventional sound reproducers. In the Predators exhibition at the Natural History Museum clear, tri-wall polycarbonate panels were sited above the animal exhibits to add scarily realistic surround sound effects.

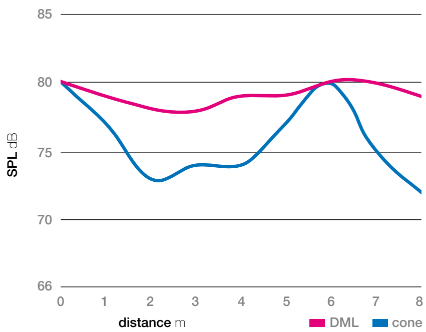
The better maintained, more uniform directivity of NXT panels also has the benefit of reducing the disparity in sound intensity between different parts of an auditorium. As well as improving sound quality for the audience in general this can reduce the overall loudness requirement, thereby reducing the risk of ear damage that can result from prolonged exposure to high-intensity sound.

11 architectural

Many modern buildings require sound distribution systems to carry music and voice messages. Uniform sound distribution and good intelligibility are key requirements in these circumstances but the use of visible loudspeakers is often unwelcome.

Because they can easily be disguised as ceiling tiles or picture panels, NXT loudspeakers are able to meet the core acoustic requirements while not intruding on the aesthetics of an architectural space. Because of their superior coverage figure 26

figure 26 **coverage with distance**
DML vs cone at 6m separation



NXT ceiling speakers can also reduce the number of speaker units required in a given space. This, together with the essentially simpler construction figure 27 and lower cost of individual panels, can bring significant cost savings.

figure 27 exploded diagram of the PA3 developed by NXT to demonstrate the potential of DML panels in public address applications

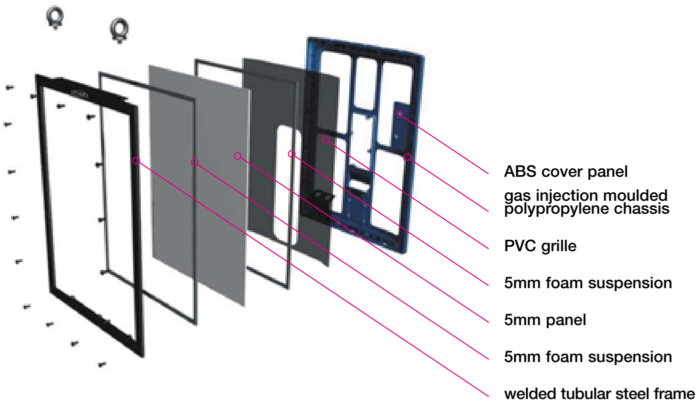


figure 28a ccf frequency response pa1 panel

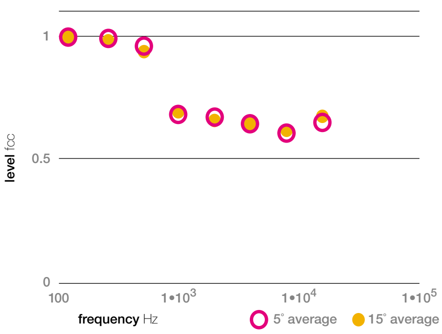
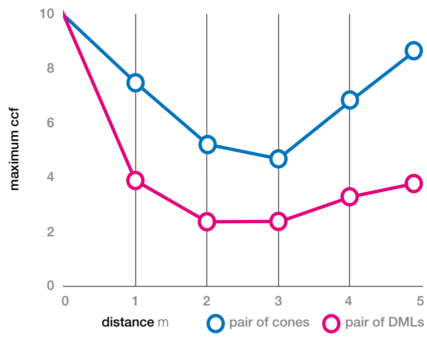


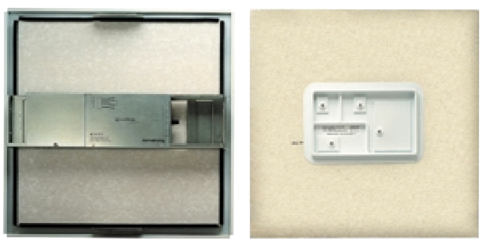
figure 28b ccf vs distance
DML vs cone (250Hz-4kHz)



In large open-plan offices loudspeakers are also commonly deployed to provide sound masking: a low level of random noise that helps suppress disturbance due to telephone conversations or other sounds originating nearby. When this noise is generated using conventional, pistonic loudspeakers the correlated nature of their output would lead to comb filtering effects that could be heard when moving through the space. To combat this, conventional sound masking speakers have to be mounted behind the ceiling tiles, which means they cannot readily be used also to deliver PA.

Because the radiation of NXT panels is diffuse over much of the audible frequency range figure 28a and this characteristic diffuseness is retained when multiple panels are employed figure 28b, comb filtering effects are suppressed. This allows NXT ceiling tiles to deliver both sound masking and PA output figure 29, a consolidation of roles that allows further cost reduction.

figure 29 Armstrong Industries' i-ceilings panels look identical to conventional ceiling tiles but operate as loudspeakers



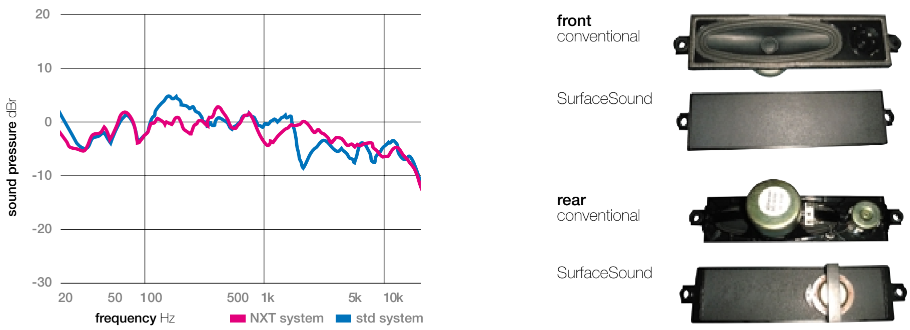
12 television

SurfaceSound and SoundVu technologies are both well suited to television applications, where they are able to provide the kind of immersive sound experience conventional TV loudspeakers cannot emulate. NXT has built television demonstrators using both technologies that comfortably outperform existing solutions. Commercial TV products using SurfaceSound panels have already come to market figure 30.

As a case study to understand the benefits of SurfaceSound technology in a television environment, a high-end 32-inch TV was converted by replacing its conventional speaker modules with NXT modules of the same footprint. In our tests, both the subjective and measured results showed significant improvement. Subjectively there was a marked advance in general sound quality and spaciousness as well as a widening of the sweet spot. The measured results fully confirmed the improvement in the overall power response of the system. Module complexity, size and cost were all significantly reduced figure 31.

figure 30 Grundig's flagship PlanaVision widescreen plasma TV incorporates SurfaceSound panels within its slim base

figure 31 a SurfaceSound demonstrator module used to replace the two-way moving coil module in an award-winning production TV, with comparison spatial average responses. The NXT installation is simpler, smaller, lower cost – and produces better sound



The particular advantages of SoundVu technology have already been described: almost zero footprint and an intimate locking of sound to picture. SurfaceSound panels lack these specific benefits, at least when applied to transmission televisions, but all the other benefits of DM operation still apply: improved stereo stability, a much wider sweet spot and more uniform loudness throughout the room. With a projection television the viewing screen itself can be a large SurfaceSound panel, in which case the locking of voice to picture is as unshakeable as it is with SoundVu technology.

Another proof of concept case study was undertaken by a ground-up design of a 22-inch flat screen television set incorporating SoundVu technology. Three front channels were combined within the radiating panel, enabling a full 5.1 surround sound system using additional rear channel SurfaceSound speakers. The acoustic performance of this demonstrator far exceeded our expectations and showed good measured power response figure 32.

figure 32 NXT's SoundVu technology-based LCD television demonstrator and its spatial average response. The panel itself has almost zero footprint; subwoofer and electronics are housed in the base

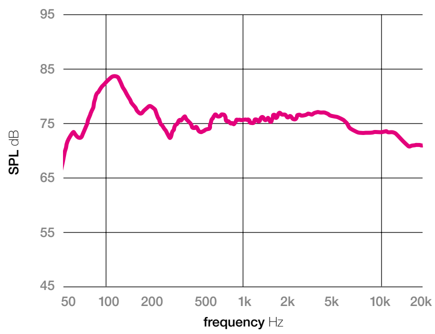
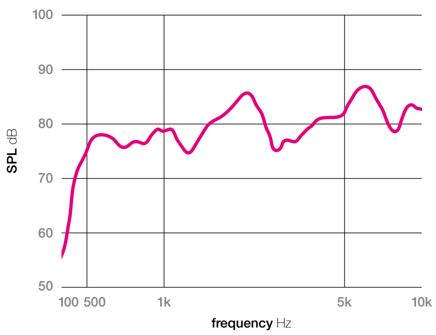


figure 33 **SoundVu technology-based mobile phone** demonstrator and spatial average response



13 telecoms

SurfaceSound and particularly SoundVu panels offer important advantages when used in place of conventional moving coil transducers in mobile phones. The hemispherical radiation pattern and low distortion transform sound quality in hands-free operation, the wide directivity allowing convenient positioning of the handset for one-to-one and conference calls.

In near-ear (privacy mode) use there is also the advantage that the listening hot-spot experienced with today's moving coil transducers is removed because of the much larger radiating area of an NXT panel. Coupling to the ear is therefore less critical. This also has the effect of reducing the intensity of sound experienced by the user if the telephone is inadvertently used close to the ear when in hands-free mode.

Industrial design flexibility is also enhanced and with the DMA actuator (see page 22) there are both space and power savings on offer. Reducing the audio transducer's power draw by increasing its efficiency brings obvious benefits to battery life figure 33.

14 automotive

High quality audio systems are a standard fitment in many modern cars. To date the motor manufacturers have relied largely on conventional loudspeakers to meet this requirement but these are less than ideal in a variety of respects.

Automotive engineers and designers are under constant pressure to reduce fuel consumption and tailpipe emissions, enhance passenger comfort and, of course, save costs. The use of NXT panels can aid all these imperatives.

Generation on generation, cars have become heavier as a result of increased equipment levels and the greater emphasis on passive safety (crashworthiness). Increasing the weight of a car has a detrimental effect on fuel economy, so car makers expend considerable engineering effort trimming weight wherever possible. High strength steels, aluminium, magnesium and plastics have been increasingly deployed to achieve this, while many manufacturers are now turning to multiplexed electrical systems to save on the substantial mass of copper used in today's complex wiring harnesses.

NXT panels assist the weight saving process by each replacing two conventional drive units (midrange and tweeter) and the crossover network required to divide the frequency range between them. In a fully integrated NXT system, further savings are possible as a result of the panels performing a dual role as trim panels. This parts consolidation is doubly attractive in that it also reduces complexity.

Achieving the maximum interior space within the vehicle's exterior dimensions is another important requirement, referred to as 'packaging'. Even a few millimetres liberated in a critical position, particularly within the doors, can make an important contribution to the actual and perceived space within the cabin. Because NXT panels are shallower than conventional drivers and can be formed into complex shapes, they offer this opportunity.

In addition to these important spin-off benefits, NXT panels also provide superior sound quality. Their wide directivity and the improved uniformity of sound power they provide within an enclosed listening space ensure that a more consistent quality of sound is maintained throughout the cabin. Adding a centre channel, with the NXT panel typically incorporated within the instrument panel, is particularly effective at expanding the sweet spot.

15 scientific infrastructure

NXT scientists and engineers have written in excess of 50 academic research papers, many of them presented at Audio Engineering Society conventions, describing and elucidating different facets of distributed-mode loudspeaker behaviour. As a result of this intensive effort to promulgate the operating principles and performance characteristics of NXT technology, the distributed-mode loudspeaker is now firmly established in the audio engineering community as a new paradigm with unique qualities.

This publishing offensive is the outward sign of what has been an intensive internal effort at NXT to understand and characterise the behaviour of DMLs as intimately as possible. Developing a mathematical description of the panel's vibrational behaviour was the key to making distributed-mode loudspeakers a practicable technology and to creating the computer-aided design and simulation tools that would allow licensees to develop DML solutions to meet specific requirements. Once the physics of DML operation had been elucidated it also became possible to begin the central, ongoing task of characterising panel materials and exciters, and assembling this information into databases. As described below, these databases form a core component of our purpose-designed computer-aided design tools.

16 manufacturing infrastructure

NXT's aim is to provide its licensees with as straightforward a route to market as possible. This means offering them a 'kit of parts' in the sense of establishing an infrastructure of panel material and exciter suppliers worldwide, whose products can be combined, as required, to develop a complete product solution. To date we have characterised over 200 different panel material constructions from 28 suppliers in Europe, the US and Far East. Today a selection of 52 different exciters is available from 12 suppliers worldwide. We consider it part of our role to create and manage the supply chain so that licensees are able to bring finished products to market using proven components from reliable sources.

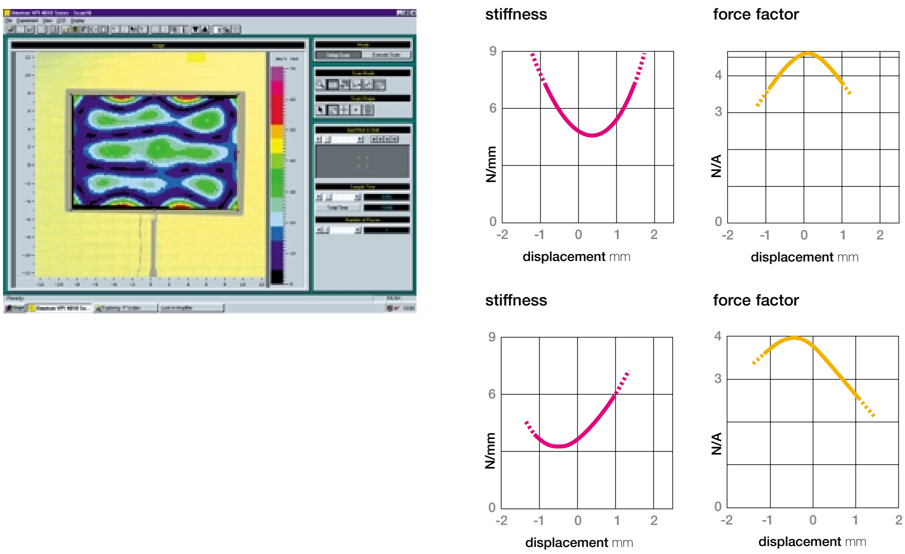
17 CAD tools

The deterministic behaviour of NXT panels allow the development of computer-aided design tools that give reliable, accurate simulations of performance prior to the building of a first prototype.

To facilitate this process we have developed and continue to refine a computer-aided design program called PanSys. The software enables speaker engineers to operate at various levels of sophistication, ranging from simple plug-in, cookbook design solutions to more complex, individual analysis of design alternatives. Finite element analysis of panel behaviour is too slow, costly and cumbersome, whereas a spreadsheet-based simulation is too crude. What product designers require is something inbetween, which is easy to use but gives accurate results in the minimum computation time. This is what PanSys provides.

PanSys is subdivided into five interlinked modules – labelled Panel, Components, Radiation, Enclosure and Simulation – which guide the user through the design and simulation process. Central to its accuracy and utility are comprehensive panel material and exciter databases which define the key physical properties necessary for accurate simulation. None of these physical characteristics is taken 'on trust' from the panel material and exciter suppliers; instead every panel material and exciter within the PanSys database has had its behaviour characterised using specialist measurement equipment installed at NXT's Technology Centre. This equipment includes a laser vibrometer to measure modal behaviour and establish the stiffness and damping of the panel material under dynamic conditions, and a Klippel analyser to perform comprehensive characterisation of exciter performance figure 34.

figure 34 panel material and exciter characteristics
are accurately and consistently quantified in-house before inclusion in the PanSys databases



Using PanSys the designer first specifies the panel material and exciter(s), then builds a virtual DML by specifying the panel dimensions and exciter position(s), wiring these up with the inclusion of any passive filters that are required. Different boundary conditions (free, simply supported or clamped) can be defined for each panel edge or a foam surround can be specified, using a database of suitable materials. Various forms of baffle can be added and an enclosure can be dimensioned if it is required to control radiation from the panel's rear face. Once construction of the virtual loudspeaker is complete, a wide variety of performance parameters can then be simulated including power response, exciter excursion, electrical impedance, directivity and panel vibration contours. The latter are particularly useful for identifying points on the panel where small masses or damping pads can be placed to control specific modes.

PanSys is updated every few months with code refinement, functionality and feature enhancements, and the latest additions to the panel material and exciter databases figure 35.

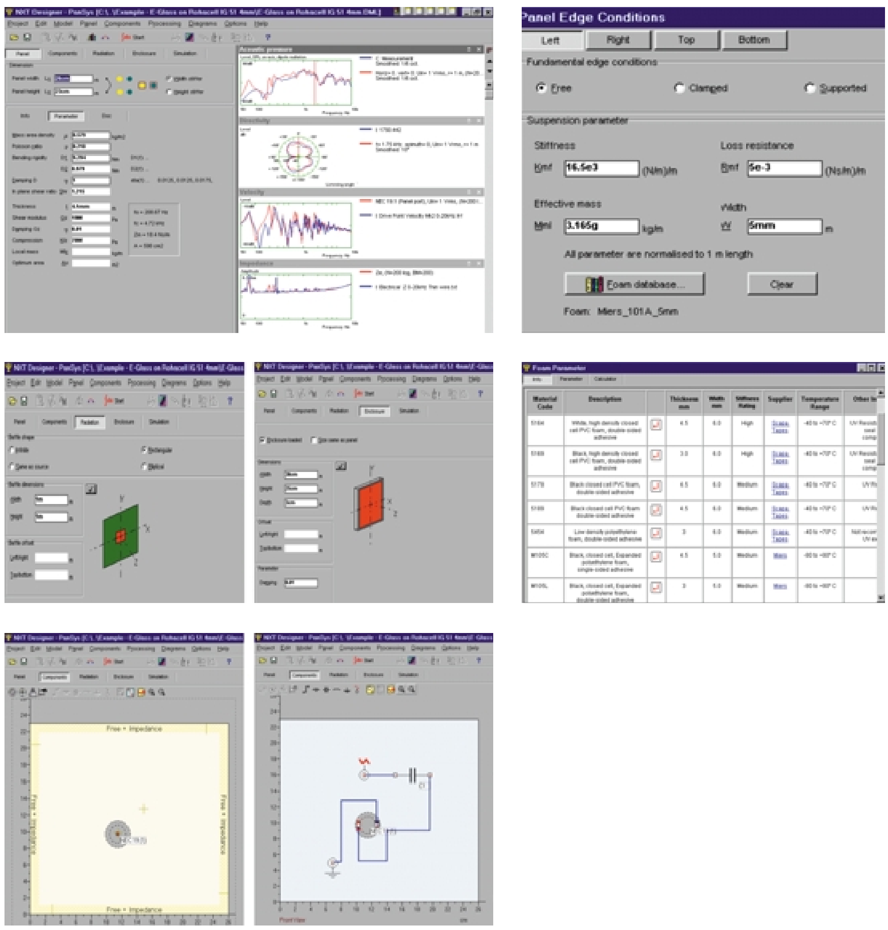
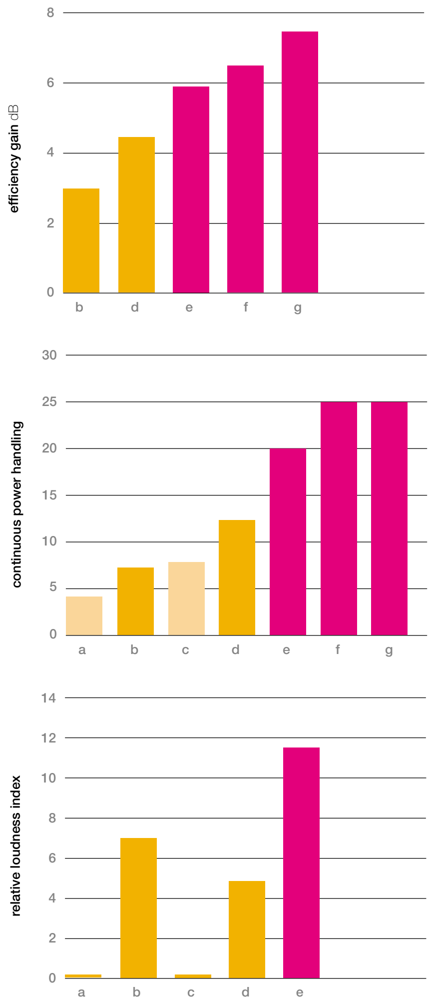


figure 35 PanSys screenshots
working backwards: simulation results (top left), specification of radiation conditions (centre left), component positioning and wiring (bottom left), edge conditions and suspension (top right), exciter and panel materials database (centre right)

figure 36 **Ongoing technology development** has elicited considerable gains in exciter efficiency, power handling and relative loudness index

a 19mm 1st generation
b 19mm concentric
c 25mm 1st generation
d 25mm concentric
e 25mm radial 15mm magnet length
f 25mm radial 20mm magnet length
g 25mm radial 35mm magnet length



18 technology development

NXT's is a growing technology base in which particular technical and product-related issues are identified and addressed on a continual basis, often in close collaboration with our industry partners. As an example, the need for more efficient exciters was identified recently to meet the higher sensitivities demanded in certain applications. This inspired an intensive investigation of all the design factors influencing sensitivity and the development of manufacturing solutions to address them. As a result of this effort, both the efficiency and power-handling performance has improved markedly in what we call second-generation exciters figure 36.

Another exciter example is the DMA piezoelectric exciter developed by NXT to meet the particular form factor and efficiency requirements of mobile phones and PDAs. Piezoelectric crystals are smart, shape-changing materials. Applying a voltage across them alters their length, allowing them to be used as a transducer. The traditional problem with using a piezoelectric actuator to drive a loudspeaker diaphragm is that it acts as a displacement device whereas what is required for a conventional loudspeaker is an acceleration device, and for an NXT panel a velocity device. This disparity can only be overcome using equalisation, which means that large voltages are required at low frequencies.

Working at our Technology Centre in Huntingdon, NXT scientists asked what would happen if a piezoelectric material were used unconventionally, within its modal (*ie* resonant) region. The answer turned out to be that it becomes a modal velocity transducer, ideally suited to driving the modal panel within an NXT loudspeaker.

The DMA comprises one or more small beams of piezo crystal, connected at a common stub which forms the panel forcing point. The drive is inertial but many times more efficient than can be achieved with a moving coil exciter. DMA is also much shallower than a moving coil equivalent, saving space and providing improved panel output response to higher frequencies.

As well as working closely with our licensees to develop technical solutions to meet particular application requirements, we continue to work on cost and value engineering issues. We have made significant strides in reducing the implementation costs of all our technologies, and that effort continues.

19 intellectual property

Innovation is a core value at NXT and this mindset has produced a significant number of inventions and patents since our launch. Building on the original 21 patents, over 150 single inventions have been filed in the last five years, which are at various stages of examination and grant. Today a total of 450 patents have been granted with a further 1250 pending. Our continued innovations and patent filings fill-in, add to, strengthen and consolidate our unique flat-panel loudspeaker technology, while extending the validity date of the NXT IP beyond the year 2015, when our original patents are due to expire. This in turn will ensure solid royalty revenue income for the company going forwards in the foreseeable future.

20 technology transfer

All NXT licensees receive extensive training in our technology, and the dissemination of our know-how and IP is backed up by the publication of general and application-specific technical notes. But these represent only a small part of our technology transfer effort. We aim to build close, ongoing relationships with licensees so that as well as offering them existing solutions we can learn about and address the specific design and implementation issues they face in each application area. The identification of performance targets and design challenges within each market sector allows us to address these requirements using the technical and intellectual resources of NXT's Technology Centre figure 37.

To emphasise this customer-centred approach our Technology Transfer division is now divided into business units, each of which specialises in a particular area of application. Engineers and scientists attached to each division are able to assist licensees with product development issues and, if necessary, undertake directed research to resolve a particular problem.

Over and above this, NXT offers a complete product and application consultancy service. Our Technology Centre has extensive performance evaluation, rapid prototyping and industrial design capabilities so it can, if required, develop products from concept right through to full production drawings and bills of materials, via working prototypes figure 38.

Our stated company vision is "To help our customers win through superior technology" and we believe we have assembled the human resource, the facilities and the scientific and manufacturing infrastructure to deliver on that.

figure 37 identification of performance targets and design challenges within each market sector drives the research process at NXT's Technology Centre

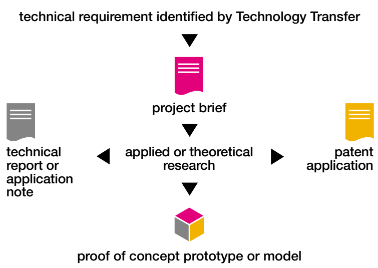
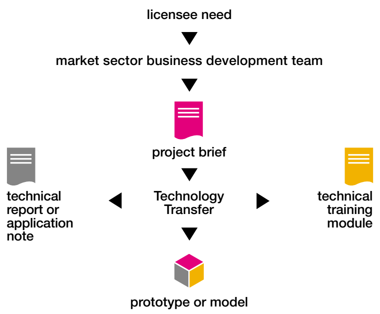


figure 38 a complete product and application consultancy is also available



21 new developments – TouchSound technology

NXT's ongoing research effort is primarily devoted to extending the capabilities and reducing the implementation costs of our principal technologies, SurfaceSound and SoundVu. Within this process, however, further product potentials are sometimes identified which open up entire new areas of application. TouchSound technology is an example.

TouchSound technology is a development that extends the multi-functionality of a SoundVu screen still further so that it doubles both as a loudspeaker and as a touch-sensitive input device. The same technology can also be applied to SurfaceSound panels to combine the loudspeaker and input functions.

TouchSound technology works in a way broadly comparable with radar location. When a finger is placed on the screen or panel, it changes its vibrational behaviour. By detecting this change in vibrational behaviour, it is possible to determine the coordinates of the finger's position to a high degree of accuracy. Control logic then initiates the appropriate machine response. Matters are complicated by the dispersive nature of bending wave propagation (propagation velocity is frequency dependent) but this is corrected by the use of digital signal processing figure 39.

Although TouchSound technology is in the early stages of development it already demonstrates great promise. Resolution of better than 1mm has been achieved in the early PDA-sized prototypes. TouchSound technology functionality employed within a SoundVu application confers other tangible advantages. Unlike most touch-screen technologies TouchSound technology does not deteriorate the transparency of the screen, resulting in a superior visual performance. Although extra transducers are sometimes required, much of the necessary hardware is already present in a SoundVu application for sound generation, so the implementation cost can be low. The complexity of TouchSound technology resides mostly in the physics and the processing software, which can be simply accommodated within the existing processing capability of laptops, PDAs and mobile phones, or through its own dedicated control ASIC.

figure 39 how a TouchSound screen detects contact position dispersive wave propagation through the panel (left) is corrected using DSP techniques, allowing the reflection from the contact point to be identified (right)

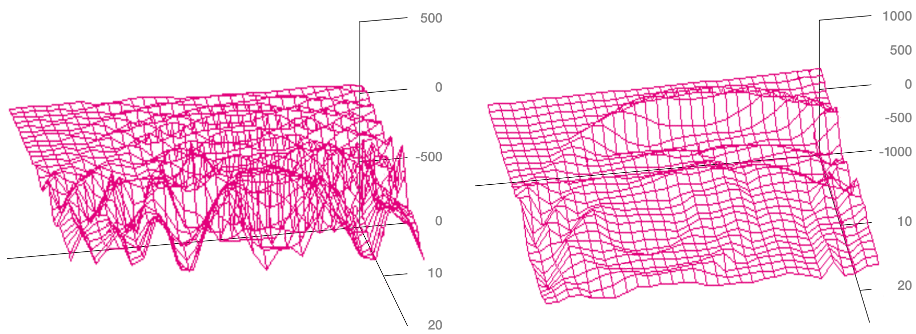
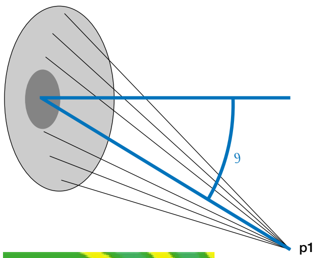


figure A1/2 soundfield (FE simulation)
from 160cm piston 2-6kHz



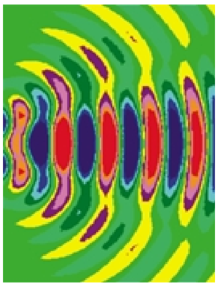
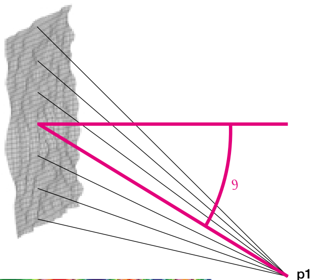


figure B1/2 soundfield (FE simulation)
from NXT panel 160cm 2-6kHz



Distributed-Mode Operation

We refer to NXT panels as distributed-mode loudspeakers based on their principle of operation. The diaphragm of a distributed-mode loudspeaker vibrates in a complex pattern over its entire surface. Close to the diaphragm, the sound field created by this pattern of vibration is complex also, but a short distance away it takes on the far-field characteristics of DML radiation. This is close to the directivity of a true point source – *ie* approaching omnidirectionality – even when the diaphragm is quite large relative to the radiated wavelength.

How is it that a panel vibrating in a complex, quasi-random fashion can radiate sound evenly in all directions? Let us distinguish two extremes of the velocity distribution across a diaphragm surface. At one extreme is the rigid surface in pistonic motion, where the magnitude and phase of the motion is constant across the surface. In this case, directivity depends only on the path length between each small element of the diaphragm and the receiving point figure A1. At radiated wavelengths that are small relative to the diaphragm dimensions, interference takes place between the radiation from different regions of the diaphragm, and this increases in severity off-axis. So the characteristic radiation pattern exhibits strong beaming figure A2.

At the other extreme, in a randomly vibrating panel, diaphragm velocity is randomly distributed with respect to magnitude and phase. The disparity in path length between different areas of the diaphragm and the receiving point is still present, but because there is now no correlation between the source points' outputs, there can be no global interference figure B1. Hence the radiated sound is dispersed evenly in all directions. Diffuse radiation of high order figure B2 becomes omnidirectional in the far field.

An NXT panel closely approximates a randomly vibrating diaphragm and therefore behaves similarly. Distributed-mode operation thus guarantees consistent output level and undistorted time response in all directions. In other words, all the radiated energy appears to originate from a single point. Despite this, a distributed-mode loudspeaker is able to produce high broadband acoustic power because its diaphragm is not constrained with respect to size. With pistonic diaphragm motion, on the other hand, these characteristics are mutually exclusive.

22 appendix – further reading

NXT conference papers

1997

AES 103rd Convention, New York, 26-29 September

1 **The Distributed-Mode Loudspeaker as a Broad-Band Acoustic Radiator** (Preprint #4526)
Harris and Hawksford

2 **A New Flat Panel Loudspeaker for Portable Multimedia** (Preprint #4527)
Tashiro, Bank and Roberts

3 **Diffuse Field Planar Loudspeakers in Multimedia and Home Theatre** (Preprint #4545)
Colloms and Ellis

4 **Improvements in Intelligibility through the Use of Diffuse Acoustic Radiators in Sound Distribution** (Preprint #4634)
Mapp and Colloms

5 **Boundary Interaction of Diffuse Field Distributed-Mode Radiators** (Preprint #4635)
Azima and Harris

IOA Reproduced Sound 13, Windermere, 23-26 October

6 **An Introduction to Distributed-Mode Loudspeaker (DML) Technology**
Azima
Note: this paper does not appear in the Proceedings

7 **A Simple Electro-Mechanical Model of the Distributed-Mode Loudspeaker (DML)**
Harris

1998

AES UK Conference: The Ins and Outs of Audio, London, 16-17 March

8 **The Distributed-Mode Loudspeaker – Theory and Practice**
Bank and Harris

AES 104th Convention, Amsterdam, 16-19 May

9 **Stereophonic Localization in the Presence of Boundary Reflections, Comparing Specular and Diffuse Acoustic Radiators** (Preprint #4684)
Harris, Flanagan and Hawksford

10 **Diffuse Field Distributed-Mode Radiators and their Associated Early Reflections** (Preprint #4759)
Azima and Mapp

11 **Distributed-Mode Loudspeaker Simulation Model** (Preprint #4739)
Panzer and Harris

12 **The Intrinsic Scalability of the Distributed-Mode Loudspeaker** (Preprint #4742)
Bank

13 **Exciter Design for Distributed-Mode Loudspeakers** (Preprint #4743)
Roberts

14 **Distortion Mechanisms of Distributed-Mode Loudspeakers** (Preprint #4757)
Colloms, Gontcharov, Panzer and Taylor

15 **Evaluation of Distributed-Mode Loudspeakers in Sound Reinforcement and Public Address Systems** (Preprint #4758)
Mapp and Gontcharov

AES 105th Convention, San Francisco, 26-29 September

16 **Distributed-Mode Loudspeaker Radiation Simulation** (Preprint #4783)
Panzer and Harris

17 **Stereophonic Localization in Rooms, Comparing Conventional and Distributed-Mode Loudspeakers** (Preprint #4794)
Harris, Flanagan and Hawksford

18 **Improvements in Acoustic Feedback Margin in Sound Reinforcement Systems** (Preprint #4850)
Mapp and Ellis

IOA Reproduced Sound 14, Windermere, 22-25 October

19 **Stereophonic Localisation in Rooms, Comparing the Distributed-Mode Loudspeaker (DML) with Conventional Two-way Cone-based Loudspeakers**
Harris and Flanagan

20 **Improving the Gain Before Feedback Margin in Video-Teleconferencing and Closed Loop Electroacoustic Systems**
Mapp

Tonmeistertagung, Karslruhe, 20-23 November

21 **DML - Distributed-Mode Loudspeaker. Ein neuer Schallwandler, akustische Eigenschaften und die Konsequenzen für den praktischen Einsatz (DML - Distributed-Mode Loudspeaker. A New Transducer, Acoustical Properties and the Consequences in Terms of Practical Use)**
Ferekidis

1999

137th Meeting of the Acoustical Society of America, Berlin, 15-19 March

22 **Improvements in Teleconferencing Sound Quality and Gain Before Feedback through the Use of DML Technology**
Mapp and Azima

AES 106th Convention, Munich, 8-11 May

23 **Loudness: A Study of the Subjective Differences between DML and Conventional Loudspeakers** (Preprint #4872)
Flanagan and Harris

24 **Distributed-Mode Loudspeakers (DML) in Small Enclosures** (Preprint #4987)
Azima, Panzer and Reynaga

25 **Improvements in Acoustic Feedback Margin in Sound Reinforcement Systems** (Preprint #4978)
Mapp and Ellis

26 **Measurement Aspects of Distributed-Mode Loudspeakers** (Preprint #4970)
Gontcharov, Hill and Taylor

AES 107th Convention, New York, 24-27 September

27 **Modal Network Solver for the Simulation of Complex Mechanoacoustical Systems** (Preprint #5022)
Panzer and Kavanagh

28 **The Scalability of the Distributed-Mode Loudspeaker (DML) in an Infinite Baffle** (Preprint #5013)
Bank

29 **Measurement and Simulation Results Comparing the Binaural Acoustics of Various Direct Radiators** (Preprint #5015)
Harris and Hawksford

30 **Investigation into the Relationship between Subjective Loudness and Auditory Distance Perception** (Preprint #5049)
Flanagan and Taylor

31 **The Complex Loudspeaker-Room Interface, Some Further Insight** (Preprint #5059)
Mapp, Azima and Gontcharov

32 **A Novel Approach to Sound Distribution in a Reflective Environment** (No Preprint)
Mapp

IOA Reproduced Sound 15, Stratford, 18-21 November

33 **Distributed-Mode Loudspeakers in Sound Reinforcement Design - Some Case Histories**
Mapp and Ellis

34 **The Loudspeaker-Room Interface, Some New Perspectives**
Mapp

35 **Distributed-Mode Loudspeaker Radiation Simulation**
Panzer and Harris

2000

AES 108th Convention, Paris, 19-22 February

36 **Diffuse Field Radiators in Automotive Sound System Design** (Preprint #5163)
Roberts, Grieco and Ellis

37 **Diffusivity Properties of Distributed-Mode Loudspeakers** (Preprint #5095)
Gontcharov and Hill

AES 109th Convention, Los Angeles, 22-25 September

38 **Measurement and Simulation Results Comparing the Acoustics of Various Direct Radiators in the Presence of a Dominant Specular Reflection** (Preprint #5215)
Harris, Gontcharov and Hawksford

39 **A New Approach To Speaker/Room Equalization** (Preprint #5221)
Chiao, Harris and Kyriakakis

IEEE Proceedings – Circuits Devices Systems, Vol 147, No 3, 153-157, June 2000

40 **Introduction to Distributed-Mode Loudspeakers (DML) with First-Order Behavioural Modelling**
Harris and Hawksford

140th Meeting of the Acoustical Society of America, Newport Beach, 1-8 December

41 **Far-Field Radiation from a Source in a Flat Rigid Baffle of Finite Size**
Panzer

27th Deutsche Arbeitgemeischaft für Acoustik (DAGA) 2001, Hamburg, 26-29 March

42 **Theoretische und Praktische Aspekte für den Entwurf von Dipollautsprechern (Theoretical and Practical Aspects of Dipole Speaker Design)**
Ferekedis

43 **Anwendung der BE Methode auf die Berechnung der Astrahlung von Kreissymmetrischen Membranformen (Application of the Boundary Element Method for the Calculation of Radiation of Circular-symmetric Diaphragms)**
Panzer

IOA Reproduced Sound 17, Stratford, 16-18 November

44 **Far-field Radiation from a Source in a Flat Rigid Baffle of Finite Size**
Panzer

2001

AES 110th Convention, Amsterdam, 12-15 May

45 **Sound Power – the Forgotten Loudspeaker Parameter**
(no AES reprint – see IOA paper below)
Mapp

IOA Reproduced Sound 17, Stratford, 16-18 November

46 **Sound Power – the Forgotten Loudspeaker Parameter**
Mapp

AES 111th Convention, New York, 30 November-3 December

47 **Spatial Bandwidth of Diffuse Radiation in Distributed-Mode Loudspeakers**
(Preprint #5412)
Harris

48 **Improving the Intelligibility of Aircraft PA Systems** (Preprint #5431)
Mapp

142nd Meeting of the Acoustical Society of America, Seattle, 3-7 December

49 **Improving the Intelligibility of Aircraft PA Systems**
Mapp

independent papers

1999

AES 107th Convention, New York, 24-27 September

50 **Distributed-Mode Loudspeaker Polar Patterns** (Preprint #5065)
Angus

51 **Evaluation of Spatial Sound Localisation Performance of Diffuse Acoustic Radiator** (No Preprint)
Foo, Hawksford and Hollier

IOA Reproduced Sound 15, Stratford, 18-21 November

52 **Radiation Mechanisms in DML Loudspeakers**
Angus

53 **An Experimental Screening Room for Dolby 5.1**
Newell, Castro and Holland

2000

AES 108th Convention, Paris, 19-22 February

54 **Distributed-Mode Loudspeaker Radiation Mechanisms** (Preprint #5164)
Angus

55 **On the Applicability of Distributed-Mode Loudspeaker Panels for Wave Field Synthesis Based Sound** (Preprint #5165)
Boone and Bruijn

AES 109th Convention, Los Angeles, 22-25 September

56 **Stereo Acoustic Echo Cancellation for Sound Spatialisation Using Pair-Wise Loudspeakers with Cross-Talk Cancellation** (Preprint #5189)
Bainbridge, Hawksford and Hughes

57 **Design of High-Quality Studio Loudspeakers Using Digital Correction Techniques** (Preprint #5200)
Horbach

58 **Distributed-Mode Loudspeaker Resonance Structures** (Preprint #5217)
Angus

59 **The Influence of Loudspeaker Type on Timbre Perception** (Preprint #5226)
Flanagan and Moore

IOA Reproduced Sound 16, Stratford, 17-19 November

60 **Modelling DML Panels Using Classical Plate Theory**
Avis and Copley

2001

AES 110th Convention, Amsterdam, 12-15 May

61 **The Effect of Porous Materials on the Acoustic Response of DML Panels** (Preprint #5324)
Prokofieva, Horoshenkov and Harris

62 **Graphical Elicitation Techniques for Subjective Assessment of the Spatial Attributes of Loudspeaker Reproduction – A Pilot Investigation** (Preprint #5388)
Ford, Rumsey and de Bruyn

AES 111th Convention, New York, 30 November-3 December

63 **The Active Listening Room Simulator: Part 2** (Preprint #5425)
Naqvi and Rumsey

64 **The Effect of Loudspeaker Type on the Identification of Vowel-Like Harmonic Complexes** (Preprint #5456)
Flanagan and Moore

published textbook

2001

March

65 **Loudspeaker and Headphone Handbook** (Focal Press, ISBN 0240515781)
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