# *Development of the Signature 800*

B&W

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Development of the Signature™800

Appendices

# *Introduction*

Signature™ speakers from Bowers and Wilkins have always been distinguished by a combination of state of the art technology, stunning design and exquisite finish. Celebrating the company's 35th anniversary, the Signature™800 is no exception.

The technology of the Signature™800 can be traced directly to the Nautilus™ loudspeaker, itself the result of a 5-year development programme. The technologies and techniques used in the Nautilus™ were further modified and developed in the design of the Nautilus™801 and the other products in the Nautilus™800 Series. That Series redefined the high-end audio speaker market, raising the level of performance and combining it with an interesting and attractive design, and resulted in a doubling of turnover in that sector of the company's activities.

However, one must always strive to improve and refine the level of performance whenever possible in order to advance the state of the high-end audio art; no product is ever perfect. At the high-end, one must also pay great attention to the level of finish and presentation of the product. It is, after all, a piece of furniture that must echo the quality of other pieces that might surround it.

The Signature™800 is simply the result of attention to detail.

**PROJECT BRIEF**

In simple terms, the brief for the product was to refine the performance of the Nautilus™801 and provide an enhanced visual design incorporating higher quality finishes.

The final design of the Nautilus™801 owed much to collaboration with EMI Abbey Road Studios in London. The speaker was required to deliver an extended and responsive bass performance to high replay levels. This it can do with ease, but the studio environment bestowed the benefit of a well-controlled acoustic. In less than ideal domestic situations, more prone to room resonances, the bass could sometimes seem overpowering. In such circumstances, the Nautilus™802 could often deliver a better balanced sound, but not to such high replay levels nor reach quite as low in frequency. Part of the brief for the Signature™800, therefore, was to be able to deliver the output of the Nautilus™801 but with an alignment that was more suited to real life domestic environments.

One of the outstanding features of the Nautilus™801 is its ability to create an uncannily realistic sound stage. It is the difference between painting an audio portrait and actually being able to imagine the performers are right there in front of you. To achieve this requires several aspects of the design to come right all at the same time. The geometry of the enclosures plays a part and the Signature™800 obviously takes its cues from the Nautilus™801 in that respect. But it is also important to minimise the effects of both linear distortions (those that are present at all replay levels and often described as coloration) and non-linear distortions (those that increase as the level increases). All these distortions serve to add a character to the sound that has nothing to do with the original signal and serve to reduce the speaker's ability to resolve fine detail. Their source is to be found in almost every part of a speaker's structure and it is only by attending to the smallest details in the drive units, enclosures and crossover that one can begin to approach the levels of performance that were demanded of the new design. Some of the information incorporated in this paper has already been published in the document "Development of the Nautilus™801 Loudspeaker". However, it was felt preferable to be able to use this paper without reference to earlier publications.

## DRIVE UNITS

### Tweeter

In most respects, this drive unit is identical to that used in the Nautilus™801. The unit operates over a fairly narrow frequency range (from 4kHz up) and a stiff pistonic diaphragm, loaded by a tapered tube is applicable. Indeed, with the advent of the high sampling rate recording formats DVD-A and SACD, a stiff diaphragm is the only option for extending the response of a standard moving coil drive unit into the ultrasonic band.

At this point it is worthwhile to discuss the requirements of these new recording formats a little, because what are popularly regarded as being the optimum requirements for compatible drivers do not coincide with our own in all respects.

The response of human hearing generally falls off rapidly above around 22kHz. A small proportion of the population can detect tones at higher frequencies and older people suffer a reduction in the cut-off frequency. One may therefore reasonably ask what possible point is there in attempting to reproduce frequencies up to 100kHz. The answer lies, not in reproducing amplitude to very high frequencies, but having the ability to ameliorate the phase and group delay ar

### Midrange

At first sight 'perfect piston' drive units, (ie those that move solidly without bending and with a total freedom from resonances), would appear to satisfy the ultimate requirement for perfect sound reproduction. That is, within their linear motion limits they add nothing to the sound and take nothing away – they simply reproduce exactly at all frequencies, but will also be coupling into the rest of the room, via its radiation in other directions, in a similar manner at all frequencies. (ie: Its energy response as distinct from its on axis frequency response will be more nearly constant with frequency).

The problem with the Signature™800, as with the Nautilus™801 before it, is that the midrange drive unit has to be large enough to deliver high sound levels in the low hundreds of hertz, yet operate over a relatively wide bandwidth. This would bring into play all the limitations of the stiff diaphragm approach to design. One must therefore opt for the controlled break-up approach.

Woven Kevlar® has proved to be an outstanding diaphragm material, when correctly doped with resins and damping compounds (see appendix I). Nevertheless, it was felt that improvements could be made to the performance of existing units.

Laser measurements had shown that, although the cone behaviour was improved by using Kevlar®, the behaviour of outer roll surrounds, which provide a significant proportion of the total radiating area, still left much to be desired. In particular, a phenomenon known as the 'surround resonance' tends to occur right in the middle of the midrange. This phenomenon actually comprises two closely spaced resonances.

All resonances in the cone / surround combination can be thought of as standing waves. These start out as bending waves generated at the voice coil, moving up the cone to the outer edge, where they are reflected to move down the cone back to the voice coil. Here they may be reflected again and so on. If a whole number of wavelengths exactly fits into this 'out and back' path, peaks in the wave on the way out coincide with peaks in the returning wave and a resonance or standing wave results. In a single continuous material, the standing wave patterns of the two lowest modes are the familiar shapes shown in figures 2a and 2b. The proportions change somewhat in the case of a cone attached to a surround. The cone is relatively stiff. It will therefore not bend very much and the bending wave velocity is much higher than in the relatively much more flexible surround. The modified modal patterns are shown in figures 2c and 2d. The position of the minimum movement node is nearer the cone surround junction because of the faster bending wave velocity in the cone material.

The lower frequency resonance results in a peak in the steady-state amplitude response, when the outer edge of the cone and the surround both move more than they would in the simple pistonic motion case, but in the same direction. The higher frequency resonance involves the cone body moving more than it should in the normal direction while the surround moves in the opposite direction. This may result in a peak, dip or no change in the amplitude response depending on the relative area velocity of the cone and surround.

Laser progression plot measurements confirm that the velocity of bending waves from the voice coil to the surround are the right order of magnitude for this to be the correct explanation for this phenomenon. Measurements of a very stiff metal cone speaker (Fig. 3) clearly show up both resonance frequencies, the lower peak at point (a) and the dip at point (b). Higher harmonics of this standing wave system will appear at higher frequencies than those shown here.

In fact all speakers with relatively flexible surrounds show this fundamental mode behaviour. However, it is not usually spotted from the response curve because it may only slightly affect the level to the order of 0.5dB or so. Laser plots, when taken sufficiently low down in frequency, invariably show the surround moving more than the cone does at this fundamental bending wave modal frequency.

Since this is a bending wave reflection phenomenon, it can be cured in four places:

1. At the voice coil / cone junction
2. At the surround / cone junction
3. At the surround / chassis junction
4. In the material of the cone and / or the surround

Taking each of these in turn:

*At the voice coil / cone junction*
Associated with all wave transmission mechanisms there is a so-called characteristic impedance. A good analogy is a TV antenna coaxial cable, where the characteristic impedance is 75Ω. If the end of the TV cable is terminated with a 75Ω resistive load, no energy will be reflected back down the cable at all. ( The standing wave ratio will be zero). If the cable is shorted out completely, no energy is absorbed at all and 100% of it is reflected back, but out of phase with the incoming wave. Conversely, if the cable is left completely open circuit (ie nothing is attached to it at all) all the energy will be reflected again, but this time it will be in phase with the incoming wave. Thus as you change the load from just below to just above the characteristic impedance, the phase of the reflected wave will change by 180° and, more importantly, the conditions for standing waves to form will be altered and the resonance will now occur at a significantly changed frequency, much lower in the ‘shorted out’ case.

With speaker cones the characteristic impedance to bending waves at the voice coil is affected by the coil mass. As the changes in mass take the bending waves towards their characteristic impedance, the surround resonance amplitude falls to zero at exact impedance matching. Then the frequency at which the surround resonance occurs will change significantly by, and be determined by, the half wavelength that the impedance change represents, and its amplitude will then increase as the impedance is altered further in the same direction. This is a major change indeed. If bending waves were not dispersive (ie if their speed did not change significantly with frequency) the frequency of the surround resonance would be doubled. Since they are dispersive however, the frequency is changed by a factor closer to $\sqrt{2}$ instead.

*At the cone / surround junction.*
The effect of this junction is more complex. If the bending wave impedances are the same on both sides of the junction, the wave will pass through without reflection. However, damping placed at the junction can absorb some of the energy as it passes through.

If the junction represents a short circuit, then all the energy will be reflected back out of phase and none will pass into the surround at all. Standing waves will then form in the cone on its own and will occur when the phase changed wave fits into the cone’s radial dimensions.

If the junction represents an open circuit (ie if the Impulse Progression plots show that this is not often the case, so usually this technique yields disappointing results.

*In the cone or surround material.*
If the bending waves can be absorbed anywhere in the system, this standing wave phenomenon will be cured. This can be done by improving the damping within the cone material itself. Furthermore this has the added bonus of damping out the more usual cone resonances as well (ie those standing waves in the cone only – not in the combination of cone plus surround which we are considering here).

Experimentation with different resin mixes for Kevlar® cones has shown this most markedly. A slight limitation to this damping approach is that the frequency response of cones with excessive damping, and probably lower stiffness as a consequence, will not be so well maintained to higher frequencies. There is also another negative effect from making the surround material too lossy – especially for bass cones – and that is that they lose their ‘punch’ or ‘attack’. This is because a highly damped surround tends to be more massive than a less damped one and has poor resistance to deformation under the effects of pressure within the cabinet. This means that their mass tends to delay the initial acceleration of certainly the outer regions of the cone and possibly the whole cone in response to an input impulse. The effect is a perception of slow, unexciting bass when a highly damped surround is used in a bass unit, and a limited higher-frequency response when it is used in a midrange unit.

## SUMMARY

- The so-called surround resonance is nothing more than the first harmonic of the overall coil / cone / surround bending wave resonance phenomenon, when exactly one complete bending wavelength will fit into the combined distance from coil to chassis.
- The fundamental of this resonance always exists, but usually goes unnoticed since it only marginally affects the steady state response.
- So-called break up resonances of the cone and the surround are the result of the remaining harmonics of this phenomenon.
- The resonances may be cured in a combination of at least 4 different ways, possibly the best one being to match the impedances at the cone surround junction and lead the energy in to the surround to be totally absorbed if possible.
- Similar phenomena occur for each wave type or propagation mode.

Fig 4 illustrates the surround behaviour showing the motion continuing for a long time after the input impulse has ceased.
Note that:

- The impulse travels rapidly to the surround.
- The surround carries on slowly oscillating long after the impulse has passed.
- The two curves shown here illustrate the surround in an upwards and a downwards movement.

This graphically illustrates how surround resonances can carry on radiating long after the impulse (and therefore the music) has ceased. This greatly colours the sound. If the surround radiation can be removed, as in the FST midrange, the sound quality is greatly improved as a result.

Fig 5 shows a picture of a laser slice plot with low frequencies at the back and high frequencies at the front.

The “surround resonance” is seen clearly in the middle, with the cone going downwards much more than at neighbouring frequencies and the surround going upwards at the resonance, whereas it behaves properly to each side of the resonance ie it acts as a “lever arm” having no resonant behaviour of its own.

If the volume velocity from the cone wins out we get a peak in the response whereas if the volume velocity from the surround wins out we get a dip in the response. If such a resonance ever appears in the pass band then corrective measures have to be taken – eg any one of those described above.

## ELIMINATING THE SURROUND RESONANCE – THE FST MIDRANGE DRIVER

The new “surroundless” Kevlar® cone takes the work described in the midrange section and matches the impedance of the Kevlar®, to the suspension at 8 places around the circumference spaced by 45º and roughly corresponding to half way between the warp or weft and the bias directions. The surround material itself evolved with experimentation. Early tests with silicone rubber rings drastically reduced the surround resonance effect, but only gave a clue to the potential of matching the impedance, and also resulted in too high a drive unit fundamental resonance frequency. In the end an open cell PVC material having specific levels of plasticiser and cell size realised the desired parameters.

As is well shown in laser plots, the Kevlar® cone, although circular in form, behaves physically as if it were square. In line with the warp and weft, the material is at its least stiff and the bending waves travel at their slowest. In the bias direction, the material is stiffest and the bending wave velocity is at its maximum. At the interim points of matched impedance, energy is passed directly into the surround and there is no reflection. However, on either side of these points the impedance of the surround is either above or below the characteristic impedance of the Kevlar® and there are therefore two different conditions for reflection.

The reflections at points where the cone impedance is below the characteristic impedance of the surround exhibit phase reversal, and so appear at a lower frequency than those at points on the other side of the characteristic impedance match, where the waves are reflected in phase. In the far field, the peaks in the resonance pattern on one side cancel out the dips in the pattern on the other side and vice versa.

Note in this case that the surround, being of small surface area and operating in compression at the rear of the cone edge, gives rise to a minimum of radiation of itself and is devoid of the internal resonance effects that a normal roll surround would exhibit.

Bearing the above behaviour in mind when looking at single-frequency whole-cone plots of such a cone, we see that the resonances always appear to combine a bell mode (having four lobes ie 4 regions going downwards and 4 regions going upwards) with a whole series of axisymmetric modes (modes in concentric circles where each successive circle of the cone is moving the opposite way to the previous one). This means that the outer regions of the cone, when the low frequency perfect piston region is exceeded, always behave like a number of octopoles (4 point sources in phase and 4 interspersed point sources out of phase), which are very inefficient at radiating, leaving the inner regions to dominate both the on-axis frequency response and the directivity, which is consequently maintained nearly constant over a wide frequency range. (Fig 6)

This analysis will be true, only provided that the acoustic environment in which the cone unit finds itself submerged, both inside the box and externally, is symmetrical itself. If there are sufficiently strong local changes in internal acoustic impedance, such as those found in ordinary boxes, the requirements for “cancelling symmetry” will no longer be fulfilled and the performance of the cone/box combination will deteriorate. Consequently, the midrange enclosure was designed to maintain symmetry round the drive unit.

In addition to the reducing source effect described in

will deteriorate. Consequently, the m

It is perhaps important to note here that the vast improvements to bass performance resulted largely from a better appreciation of the mechanical requirements of pumping air, rather than controlling the travelling wave phenomena beyond the passband.

Pistonic motion to an elevated frequency is often seen as a panacea for good bass performance, but it is no measure of truly pistonic behaviour from DC, where simply E and not $E / r^2$ matters (where E = Youngs Modulus and r = density).

While the qualitative improvements were encouraging, the Nautilus™801 was required to have extremely high sensitivity and headroom. The new 12-inch bass drivers would play louder without audible protestation but not loud enough. Only more cone area and a larger cabinet would really suffice. Simply using two of the improved 12-inch units proved to be disappointing. Even though sensitivity and headroom were approaching the required levels, perceived scale, timing and speed were below expectations.

The psychoacoustics of bass is sometimes difficult to quantify but, particularly at high levels, the body's contribution to space and time location means that the brain is even less easily fooled. Two large drivers operating in free field conditions will produce a largely coherent wavefront comparable to a point source at a position equidistant from the two sources. Divergence from the central position will produce an anomaly in arrival times. Now place the same two drivers in an environment with at least one near field boundary at a normal to the array. The two drivers now experience different driving point impedances. Their outputs will vary in magnitude and phase and the coherency of the wavefront is now further degraded. Take into account the effects of the inconsistent directivity of a large two element line source on a multi-modal room environment, as well as a host of other reservations, and the arguments for using multiple drivers become less clear cut when large amounts of air are to be displaced in a domestic environment, and there is floor space for a single unit. A single circular cone is simply the most spatially efficient dynamic radiator available. This was part of the rationale behind the development of the 15-inch unit for the Nautilus™801. The new midrange unit was larger and thus usable to lower frequencies, meaning that the inherently lower bandwidth of a 15-inch would be adequate even in a passive application. What would be crucial to the driver's success would be its ability to function as a rigid piston, and not a collection of cone areas disjointed by flexure, much like multiple drivers. A great starting point was of course the new thick pulp cone. This was mnger

The resulting drivers had much of the breathtaking speed and depth that was required and is exhibited by the final design, but reliability of the spider-coil former assembly became a problem, as the limits of the new driver were enjoyed. Normally the card sleeves used to stiffen formers are perfectly adequate for bonding a spider to. But even with two spider glue joints spreading the load, the intense shear forces involved at high excursions were sufficient to delaminate the surface of the card and allow the spider to shift and tear from unbroken joints. Massively stiff carbon fibre filament wound former sleeves, a totally new application, were employed to solve this problem and provide still greater rigidity and robustness at the heart of the cone / coil assembly.

The traditional cotton-phenolic spider material was also supplanted, its stability and strength proving to be insufficient. A new Nomex® fibre based material was employed. The large excursions at high currents meant that even the coil lead-out wires had to be scrutinised. Long term tests proved a special braid construction to be the only choice. Together, these measures help to ensure consistent performance and reliability.

Testing on the early 12-inch prototypes had shown the dust cap to have a significant influence on quality, with hard, oversized dust caps proving to offer the best performance with pure bass. However, the dust cap dome resonance increases in relative magnitude and decreases in frequency as it is enlarged, putting an effective ceiling on the size of dust cap used in the bass of a quality three-way system. While the isolated response of a deep-coned bass driver with a minimal dust cap may be impressive, it will degrade the acoustic output of a nearby midrange source due to concavity effects, and is also troublesome to time-align, meaning that integration would otherwise be improved by a large dust cap. In answer to these problems, the Nautilus™801 bass driver uses a unique construction (the ‘mushroom’ assembly), whereby the oversized carbon fibre dome is driven directly by the elongated carbon fibre former, as well as being attached conventionally to the cone. The problem dome resonance is now minimised and shifted far out of band. The acoustic response of the entire cone assembly is also improved. The first axisymmetric cone mode is raised slightly, due to improved coupling to the coil, and the impedance mismatch reflection from the cone / surround termination is reduced, as is the surround resonance, due to the staggered wave propagation times from the coil to the cone / dome junction. The overall resistance to localised flexure is of course vastly augmented by the new construction. Radially, the cone is now effectively linked by a triangulation to the coil former, and the cross-sectional stiffness of the coil former itself is transformed as it is properly capped – another ingredient in the creation of hugely clean and tight yet powerful bass driver. (Figs 7, 8)

As mentioned above in the brief, it was not until the Nautilus™801 had been used in a much wider sample of acoustic environments than those used in the development process that the limitations of the rationale of choosing a single 15-inch bass driver became apparent. Unless the listening room is well controlled acoustically, the sheer power of the speaker can all too easily excite room resonances. Of course, all resonances serve to impair transient information, but the effect to which they become unacceptable depends on their level and frequency range. Extended experience showed that the Nautilus™801 thrived in larger rooms (especially those benefiting from a high ceiling) or highly damped rooms. Where these criteria were not met, the bass could sound somewhat overpowering and lost some of its agility – just the opposite of what the speaker was designed to deliver, and can indeed do so, given the right environment.

The fact that the smaller Nautilus™802, with its twin 8-inch bass drivers, could sometimes give preferable subjective results in less-than-ideal rooms prompted the design team to re-evaluate the use of multiple drivers. These have the effect of changing the way the bass output couples with the room compared a single driver of equivalent radiating area. Each driver is subject to the vagaries of a different set of room resonances, simply due to physical displacement. This twin driver approach was followed in the Signature™800, but with two 250mm (10-inch) units, which duplicate the radiating area of a single 350mm (15-inch) driver. The construction of these drivers follows exactly the principles of the 15-inch driver, with the addition of a copper coating to the centre pole to reduce harmonic distortion as described above for the tweeter.

In order to offset further the effects of a more resonant listening room and to compensate the less coherent wavefront of the twin drivers, the bass alignment of the system itself was made drier. This entailed the use of larger than normal magnet circuits and results in a very responsive and dynamic bass characteristic, even in less than ideal rooms, yet without curtailing the perceived bass extension.

## ENCLOSURES

### Tweeter

The unit incorporates straightforward Nautilus™ technology through the use of a tapered tube, filled with wadding attached to the rear of the unit and matching the hole through the pole (See appendix III). The exponential [illegible]

### Midrange

It was known that a simple Nautilus™ tapered tube would not work well over the bandwidth required of the drive unit (see appendix III), so other enclosure configurations were investigated. In particular, a sphere is well known to give a smooth diffraction-free enclosure shape. Initial experimentation was directed at investigating how the performance was affected by the size of the sphere and how the drive unit was mounted in it. In all cases, the spheres were constructed from a GRP outer shell, lined on the inside with Fibrecrete. A sphere of around 300mm proved to be the best size. Any larger and imaging seemed to be impaired. Any smaller and the unit sounded ‘closed in’. This is a difficult phrase to explain succinctly, but is akin to having traces of the effect obtained by cupping the hands round one’s mouth when speaking. The same effect is heard if tubes are used above the frequency of the onset of cross modes and this gave a clue as to what was happening in the sphere.

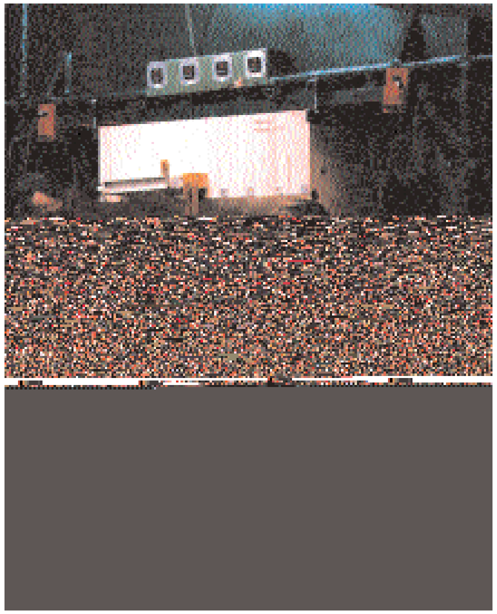
In fact the way the drive unit chassis fitted into the sphere was found to have a similar effect, which was only removed if both the inside and outside surfaces of the sphere blended smoothly with the rim of the chassis. This involved the sphere having a thin wall close to the unit and so to maintain overall stiffness of the enclosure, internal and external spherical profiles were offset, with the internal sphere centre being brought forward.

The sphere supports strong internal cross modes, evident in delayed response waterfall plots. These could only be damped by using copious amounts of wadding inside the sphere. Listening tests, however, revealed a loss of transparency with this approach, even when the waterfall plots apparently indicated a good result. The combination of a sphere and an inverse horn was then investigated both experimentally and theoretically. Measurements were made of spheres closed and open, with and without absorption being present and then with an added Nautilus™-style rear tube, which had an open end and was either empty or filled with absorption. Meanwhile some theoretical predictions of these systems were made to see which tallied with the reality.

To a reasonable degree of approximation a sphere can be modelled internally by a pipe of length and diameter equal to the diameter of the sphere and having the same volume. When this is done, the simulated cone output agrees remarkably well with the measured output for a cone in a closed sphere or a cubical box. The only difference between the tube and the sphere appears to be in the frequencies of the harmonics. In a sphere these follow Bessel function zero crossings, which are spaced differently from those in a pipe, whose resonances essentially follow a sine wave’s zero crossings. However, the form and amplitude of the response shape is remarkably similar. Exact analytic modelling of a sphere adds only a little extra accuracy to these features.

When a tube is added to the back of the sphere, the combination might be expected to behave like two tubes in series. To model this involved the modification of existing modelling routines to allow for a change in diameter at the intersection of the two tubes. Previously there had only been the possibility of a smooth join, with the end of the first tube having the same diameter as the beginning of the second tube. However, when this routine was used to simulate a sphere (modelled as a real box) with a pipe attached, the theoretical results did not tally with the experimental results at all. The resonances in the real example corresponded only to those found in the pipe part of the combination, rather than to those of the box and the pipe taken separately, and to those of the combination of the two – which the theoretical modelling showed. (Figs 10, 11, 12)

The next step, having proved that the analytic modelling tallies remarkably well with the measurements (Figs 13, 14), was to see how much the various dimensions of the tube could be pared down. Reducing the length to around 300mm and increasing the taper rate from -3 to -11 gives similar results to the long tube with minimal absorption present, though now the fundamental tube resonance frequency is shifted into the region where the ‘shorting effect’ of the lumped parameter volume reduces its amplitude. If the diameter of the large end of the tube is reduced to be smaller than that of the driver, the effect of this appears to be



## Bass

Because tube loading results in an overdamped high-pass alignment, it is not applicable to passive system bass cabinets because of the inability to add boost equalisation. Therefore, like the Nautilus™800 Series products, the Signature™800 employs a Matrix™-braced vented-box enclosure (see appendix II).

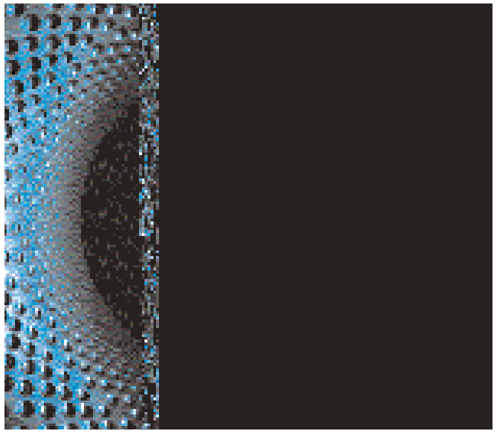
The inertness of the cabinet is further enhanced by using 38mm thick panels, also contributing significant mass. In addition, smoothly curving the rear surface greatly adds stiffness to the cabinet, and gives an interior shape which shows fewer internal acoustic resonance modes, since there are fewer parallel internal surfaces available to support the undesirable acoustic standing waves. The combination of an internal Matrix™ construction, together with both a massive and stiff external 'skin', makes the combination uniquely resistant, not only to sound transmission from inside to outside, but also to intrinsic cabinet structural modes.

Bending thin wood laminations under heat and pressure is widely used in the furniture industry for the manufacture of chairs. However the ability to accurately match and join two such curved panels together without a witness groove and to maintain the accuracy required to fit the Matrix™ panels inside is beyond the capability of many suppliers. Special storage conditions for the raw laminations, with controlled temperatures and humidity are essential and sophisticated CNC 5-axis routing machines are required to shape the edges and cut-outs of the curved panels.

## FlowPort

The movement of air in and out of tuning ports, which may represent quite a considerable physical displacement of the plug of air, often causes 'chuffing' noises as the air interacts with the discontinuities found at the internal and external ends of the port tube. These noises occur as turbulence is formed at the discontinuities. Even when the inside and outside ends of the tube are given smoothly rounded profiles, the problem is not totally cured, though it is mollified.

The reflex port is a well-established device to improve the bass response of a transducer in an otherwise sealed box of finite dimensions. As the power handling, excursion and linearity of bass drivers have steadily improved over the years, the limitations of a simple tuned port have become apparent. At low levels the behaviour of the air in the tube can be correctly approximated to a solid piston bouncing on a known air volume and at a specific tuning frequency; a readily predictable and essentially acoustic problem. At higher levels, aerodynamic effects become increasingly important and the associated loss means that a given rise in bass driver input level will yield a smaller rise in clean port output level. This also means that the port is not reducing the excursion of the bass driver as effectively and the system will thus behave increasingly like a lossy sealed box design; the combined effect is known as "port compression" and can often create an ultimate ceiling to achievable bass levels.



Well before any ceiling is reached, the energy losses associated with port compression cause problems and it is the way energy is lost rather than the amount lost that causes serious acoustic problems. At very low velocities, and with a perfect entry, air travelling through a real port tube will pass smoothly along streamlines, which do not interfere with one another. Close to the walls of the tube is a thin boundary layer caused by skin friction, with a relatively high velocity gradient. It provides the transition between the stationary walls and the moving air. Laminae of air rub against each other causing pressure drag through noiseless viscous losses. These are minimal at low levels but increase at a geometric rate in proportion to velocity. At high enough velocities, if the tube is excessively long and rough (or just very rough), the high shearing energies in the boundary layer can make it turbulent, which may be heard as wind noise, particularly because it can excite the organ-pipe resonances of the tube.

Far more serious problems occur when laminar airflow tries to leave the tube at high velocities. If the curvature of the diffuser (flare) is too sharp, the minimal momentum of the air at the base of the laminar boundary layer is insufficient to pass the resulting sharp, adverse pressure gradient without stopping or stagnation. Slightly downstream, the pressure gradient (higher velocity with lower pressure to lower velocity with higher pressure) causes the flow at the base of the boundary to reverse and a turbulent eddy is created in the form of a rotating torus (this is how smoke rings can be blown). The boundary layer now becomes the region that is between the eddy and the main flow, but it has now separated from the surface of the diffuser. It tries to follow the pressure gradient formed by the turbulence, but may form more eddies trying to do so, and so on.

The turbulent wake thus created is responsible for the 'chuffing' noises that even gently flared ports can produce under some conditions. The separation can sometimes be so extreme that a turbulent jet can hit a listener at some distance from a speaker. The aerodynamics of reflex ports is actually rather complex and somewhat unusual in that it involves alternating flow in two different pressure regimes (at and below port resonance), three octaves of the frequency spectrum (different systems have different tunings), completely indeterminate starting conditions and well over 100dB of level difference.

Aerodynamics research into reflex ports at B&W is still in its infancy. Classical wind tunnel work is very difficult because the alternating flow makes a mockery of smoke trails. Recent work with Computational Fluid Dynamics has shown that ports are very difficult to model accurately. This is partly because of the large number of variables, and also because the flow regime is influenced so heavily by small-scale turbulence creation, which is less well understood than large-scale fully-developed turbulence (more is known about how aircraft stay in the air than how midge flies do). Therefore, work has been largely empirical, using comparative rather than absolute benchmarks, because it is difficult to make reliable measurements of turbulent noise. Theoretical predictions of air velocities down the port were checked with a new Doppler measurement system, to establish the kind of flow regime operating around chuffing levels in terms of the Reynolds number (a dimensionless indicator of turbulence levels). This showed that, with care, it was possible to maintain laminar flow down the port tube, but that air could detach from the flares at fairly modest levels. Simply making the flares more gentle would not guarantee silence.

Anyone studying aerodynamics will soon learn that turbulence is not always a problem. In fact, many aerodynamicists engineer turbulence to their advantage (indeed, some aircraft would not stay in the air without it). If a boundary layer is turbulent prior to the stagnation point it will be less inclined to separate because the base layer has increased kinetic energy. This means that the surface flow can be swept further downstream before pressure conditions stagnate it and the lower pressure in the layer that results from the higher velocities within the eddies adheres the main flow to the surface profile better. Thus, small-scale turbulence can be used to delay the large-scale turbulence caused by separation.

Artificially creating turbulence in the air moving down the tube can delay the onset of chuffing to higher bass unit input levels, but problem wind noise happens far earlier, especially when turbulent air is sucked back in to the port as the flow alternates. In addition, the thickened boundary layer effectively constricts the flow, causing pressure drag and thus airflow compression. This constriction also alters the effective area of the port, which in turn affects the Helmholtz tuning. Thus it is otherwise desirable to delay the onset of turbulent flow down the tube to as high a level as possible. A more optimal solution would thus be to use a smooth tube and limit artificial turbulence creation to the problematic stagnation area. (Fig 16)

It is quite easy to produce turbulence where it is needed; aircraft use vortex generators, (vertical strakes) ahead of separation points. These strakes project into the main flow and are very effective, but when the same technique is applied to port flares it creates too much wind noise at lower levels.

Enter the golf ball. It can travel twice as far as an equivalent smooth ball because of its distinctive dimpled surface. The dimples are very carefully shaped to produce tiny separation points and favourable conditions for the creation of vortices within them. The ball is thus covered by a thin turbulent boundary layer that moves the separation point further round the ball. This decreases the ball’s wake and hence its drag, and it was this technology that was used to improve the performance of the port flares. Because a round port flare is axisymmetric, it was first thought that a series of rings with the cross section of a dimple might work (and be easier to prototype). However, the regular vortices formed simply became the new separation points and at lower levels there was audible wind noise because they were so abrupt. So real, pseudo random dimples were tried on the surface of the flare. These immediately improved the chuffing phenomenon as predicted, but there was still wind noise caused by deep dimples at the edge of the tube where flow velocities were highest. These were filled but at the expense of earlier separation levels.

A process of experimentation refined the size, shape and distribution of the dimples to maximise headroom and minimise wind noise. Small, smooth dimples are thus used where velocities are highest and larger, more abrupt dimples are used where velocities are lower. This greatly refines the exit flow regime and also ensures that a minimum of turbulence is carried back down the tube when the flow is reversed. It was found unnecessary to make the dimples totally random over the whole flare, but as long as they are locally irregular, perceptible wind noise is incoherent and unobtrusive.

In the case of the Signature™800, the port is down firing, so more wind noise is acceptable and the dimples are optimised for maximum high level flow. In use, the dimpled ports delay the nuisance chuffing noise to significantly higher levels. However, and perhaps of even greater importance, when large-scale separation does occur the resulting turbulence is far more incoherent and thus less apparent. A reduction of 6dB in certain regions of the noise spectrum was measured, particularly around the problem organ pipe frequencies. Port compression is also decreased and the tuning frequency is more stable at higher levels.

### Decoupling

Having achieved excellent cabinets for each of the drivers independently, it is important that vibrations and radiation from each driver do not leak into the enclosures of others. There now follows a brief report, which illustrates what is important when it comes to theoretical calculations of decoupling.

### The Effects of the Decoupling Spring on Speaker Performance

The effects of the decoupling spring between the magnet chassis and the speaker box have been investigated theoretically and experimentally verified. The main results of this are hardly surprising – the resonance frequency of the magnet plus chassis on the decoupling spring stiffness should be as low as possible to avoid any undesirable effects on the speaker’s response in its pass band. Also, if the resonance frequency of the magnet plus chassis on the decoupling spring, is the same as that of the speaker cone on the combined stiffness of its suspension and the air in the box, then there is no effect on the speaker’s response. This latter effect would drift in production and is probably not a desirable solution to the decoupling problem. The effects of the spring losses on the response have also been investigated.

**Method**

As in time honoured style, an equivalent circuit was derived by inspection for the three masses and three springs and one force generator, all fully floating, which this complete system comprises. The fact that all three masses were fully floating contributed to the difficulty of finding the correct equivalent circuit, because a reference to ground is always required for equivalent circuit analysis. Once a mechanical circuit had been derived, the ‘voltage’ electrical model was derived from that mechanical circuit with capacitors being equivalent to masses and inductors to springs. Then the dual of that circuit was produced to form the ‘impedance’ model, (inductors = masses, capacitors = springs), which was analysed to produce the volume velocities (ie currents) flowing into all the parts of the system. These are used to give the output response taking everything into consideration.

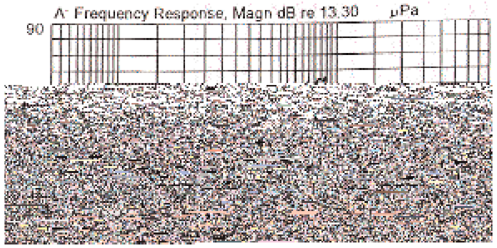
**Verification**

A simple speaker system was built comprising of a magnet and a cone of the same mass as the chassis plus the magnet. This was suspended on rubber bands to comprise a fully floating system. The nearfield sound pressure output of the cone was measured

a) with the magnet equal to the cone mass and

b) with the magnet being much heavier than the cone (which is the normal situation)

Next, the whole system was supported on a large lump of rubber and this constituted the ‘decoupling spring’ of a more normal speaker system (this test system had no box of course). The acceleration at various places in the system was also measured with a small accelerometer. The frequency responses of the accelerations of these parts of the system are related to the frequency response shapes of the volume velocities of the same parts and thus to any radiation which may take place.



**17** The results show a high degree of correspondence between the measured system and an equivalent theoretical system

Points to notice are:

- The shift of 1.414 in the basic resonance of the system when the magnet mass changes from ‘large’ to the same as the speaker cone.
- The dip followed by a peak in the cone output with decoupling spring present. The dip occurs at the frequency at which the magnet plus chassis resonates on the stiffness of the spring.
- The output of the cone at high frequencies remains unchanged over a wide range of magnet masses. This occurs because the voice coil produces a force, which it exerts equally in both directions, ie into the cone and into the magnet system. They then exhibit an appropriate acceleration according to F=M*A with F being the same in both directions and the magnet and cone masses determining the accelerations and hence the radiation from both directions.

The effect of the decoupling spring losses was then investigated. As expected when the losses are total (ie Q (decouple) very small) the system defaults to a normal speaker plus chassis plus enclosure. As Q (decouple) is increased, the dip and peak in the response become more and more pronounced. The effective Q of the lump of test rubber was approximately 20, which gave the correct ratio between peak and dip in the response. Next, a more normal speaker system was investigated and families of curves were produced varying such parameters as Q(decouple), the frequency of the magnet resonating on the decoupling spring, and so on. From these curves it becomes apparent that either the decoupling resonance should be very low, or it should be the same as that of the cone mass resonating on the combined stiffness of its suspension and the air in the enclosure. In the interests of mainting consistency of performance with variations in the driver fundamental resonance frequency, the former option was adopted.

Finally, the volume velocity being fed into the cabinet was plotted – this of course is the reason for decoupling the magnet in the first place and it should be reduced as much as possible within the pass band. Curves are shown with the decouple frequency being 1Hz and Q(decouple) being 20. It is seen that very little volume velocity is being fed into the cabinet. Comparing this when Q(decouple) is small and F(decouple) is 20 shows the size of the relative problem that proper decoupling will solve.

So decoupling is effective if it is correctly applied, the big danger being that the resonance of the magnet on the decoupling spring may fall within the pass band. If that is the case, there will be a peak and a dip in the response the size of which depends on the decoupling spring losses. Of course, the larger the losses the less effective the decoupling will be.

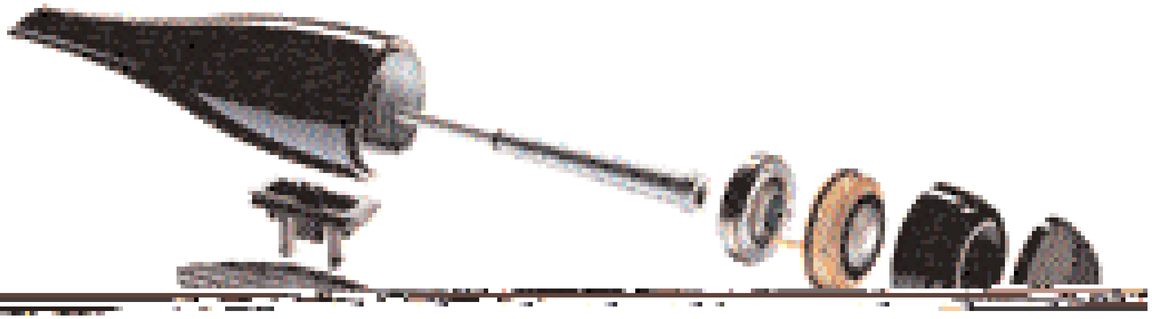
*Use of decoupling in the Signature™800*

The Signature™800 uses extensive vibration isolation to minimise cabinet resonances and driver interactions in exactly the same way as the Nautilus™801. The techniques used have drawn from B&W research work, which has shown, both theoretically and practically, the benefits of decoupling. This work has also shown how and where decoupling is best applied, as well as the problems that can arise if performed incorrectly.

Good isolation between components is relatively easy to achieve on the laboratory bench, but engineering it into a rugged product would have been far more difficult without the application of a new material. It is vital to ensure that the fundamental spring / mass resonance of any reliable decoupling scheme is below the operating frequency range of the speaker drive unit. If this is achieved then any damping control is unnecessary and even undesirable. To achieve the lowest resonance the spring must be soft and the mass must be high. The trouble has always been getting a soft spring to support a high mass within tolerances. The midrange driver isolation of the Nautilus™801, duplicated in the Signature™800, was a particular challenge and one that drove the search for new materials.

Despite the huge mass and stiffness of the midrange enclosure, decoupling the midrange driver from it produces huge reductions in cabinet vibration. However, there must be a complete seal that fits within the required acoustic shape and point contacts (fixing screws are undesirable because they unnecessarily excite higher order modes). A tensioned rod system was devised to hold the driver against the cabinet with complete axisymmetry. It was then necessary to find a very compliant material to mate them.

Foams were easily soft enough but unable to support a load long-term. Heavily plasticised materials could be found with the low Shore hardness required, but leached or crept in the long-term and were often too lossy to be effective across the band. Unfortunately, a fairly large gulf separated the hardness of these materials from the usable, homogenous, stable rubbers – even the softest silicones. Armed with an idealised specification, the purchasing team succeeded in a more extensive search for super-soft rubber suppliers.



## The Crossover

The science behind why certain crossover components sound better than others is not fully understood. That polypropylene capacitors sound better than electrolytics is well accepted and can be explained by the behaviour of the dielectric properties as the signal changes. What is not so clear-cut is why different capacitors, with ostensibly the same specification, can sound so different from one another. The difficulty in mapping physical properties to the perceived performance characteristics fur

The system may be bi-wired or bi-amplified. Provision for tri-wiring or tri-amplification was considered, but in the end was rejected. This decision was taken after market research into the way the majority of customers would actually be prepared to use the speakers. It was found that very few potential customers were prepared to have three cables to each speaker. That being the case, it is better to bi-wire with 4 terminals than 6 and have to bridge two of the pairs and introduce two redundant contacts.

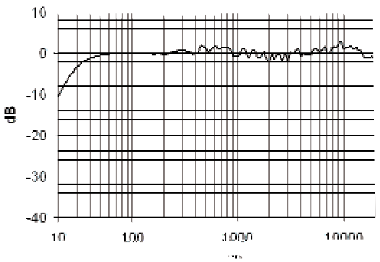
By far the dominant property of cable used for bass frequencies is the gauge. Minimising the resistance between the amplifier and the drive unit is essential to keep control. The cable feeding the bass units uses linear crystal, oxygen free copper (LC-OFC) with a cross sectional area of 6mm$^2$, equivalent to 9AWG. The cable for the mid and high frequencies remains silver coated LC-OFC, as in the Nautilus™801.

## Industrial design

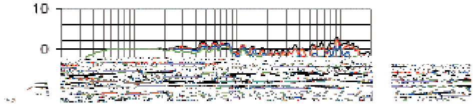
As befits its not insubstantial price, the industrial designer was briefed to produce a speaker that was in its own right a stunning piece of furniture with an exquisite level of finish. But, as the overriding priority is acoustic performance, free reign was not given for certain details of the geometry, as the two are interdependent. Thus the general shape is obviously directly derived from the Nautilus™801. However, the bass cabinet is much slimmer. Apart from making the speaker look less squat, the cabinet width is better related to the diameter of the spherical part of the midrange enclosure – one of the acoustically fixed elements of the design.

The veneer – so-called Tiger's Eye – is taken from the earlier Signature™30 speaker and sports a high gloss lacquer. The top and front of the cabinet are finished in Connolly Leather. Connolly is renowned for producing some of the world's finest leather and its products are to be found on the highest quality furniture and in the best motor cars. A cleaning fluid for the leather is supplied with the speakers.

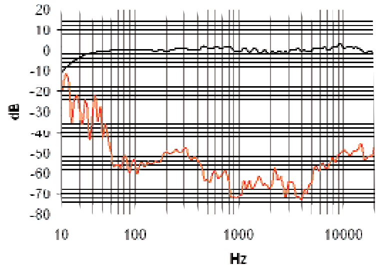
**28** Performance graphs



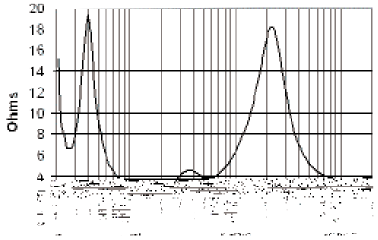
**a** Signature™800 On-axis Response



**b** Signature™800 Horizontal Response



**c** Signature™800 Total harmonic Distortion (90dB spl)



**d** Signature™800 Impedance

There is a choice of feet to support the speaker. As delivered, roller ball glides are fitted to the underside of the plinth. These facilitate movement of the heavy cabinet. However, experience with the Nautilus™801 has shown that, no matter how heavy and difficult to move the speaker seems to be, performance, especially in terms of bass slam and timing, is optimised of the cabinet is firmly anchored to the floor. To this end, the roller glides may be replaced by either spike or pad feet – the former for piercing through carpets and the latter for vulnerable surfaces such as wood.

The speaker is tall and, if the seating position is low, the optimum listening window may be directed over the heads of the listeners. The feet therefore have a good deal of adjustment that allows the speaker to be tilted forwards.

## Performance

Several aspects of the loudspeaker's performance are represented graphically in figures 28a-d. However, these graphs go only part of the way to fully describing the performance. Properties such as imaging, coloration, dynamics and bass 'speed' or 'slam' are difficult to describe graphically and can only be properly assessed through a series of listening tests.

The imaging capabilities of the speaker are extremely well developed. The usual tendency for the central image to collapse to the nearer speaker when the listener is positioned off-centre is not present, although the image does, of course, move to one side. An image between the two speakers is present even for listeners positioned outside the area between the speakers. The representation of depth is excellent where the information is in the recording and the speakers are well spaced from the rear wall.

Coloration and distortion have been improved, even compared to the already low levels of the Nautilus™801 and that in turn has improved the transparency and clarity still further. Like the Nautilus™801, the Signature™800 maintains its outstanding performance in these areas to high sound levels, which has the effect of making the speaker sound less loud than it is actually playing, as distorted sound is perceived to be louder for the same measured level.

The bass performance is suited to a wider variation in room acoustics than the Nautilus™801, which widens the applications under normal domestic conditions.

## Credits

The creation of the Signature™800 is the result of the work of a dedicated team of designers and engineers and the input of the following is recognised:

- Steve Roe BSc
  Development Director (Overall project responsibility)
- Dr Peter Fryer BSc DIC PhD
  Research Director (Laser techniques, diaphragm and enclosure analysis)
- Stuart Nevill BEng
  Research Engineer (Drive unit, Flowport, sphere/tube and decoupling design)
- Dr Gary Geaves BSc PhD
  Research Engineer (Finite Element Analysis)
- Dr John Dibb BTech PhD
  Senior Development Engineer (System design)
- Steve Pearce
  Development Engineer (System design)
- Doug Standen
  Design Engineer (Mechanical Design)
- Morten Warren
  Native Design (Industrial Design)

## APPENDIX I
## THE USE OF WOVEN KEVLAR® AS A LOUDSPEAKER CONE MATERIAL

### Introduction

We shall examine the difference in behaviour between a woven Kevlar® cone and a plastic one of similar dimensions.

### Plastic Cone Impulse progression plot (Impulse Plot)

(Fig AI-1a)

We see that

- Impulse is fed into the voice coil in middle.
- A fast Compression Wave then speeds towards the surround
- A Slower Bending Wave follows on behind
- The Bending Wave is reflected from surround like sea wave hitting a sea wall
- Reflections are rotationally symmetrical and
- carry on back and forth for a long time
- The behaviour is totally rotationally symmetrical at any time
- No dust dome was present

Note: Because the waves are rotationally symmetrical, they all add up the same way in all radial directions. Whenever half a wavelength of the bending wave fits into the space from voice coil to a reflection point, (usually the surround and / or the chassis), a standing wave (otherwise known as a resonance) is formed. This is always bad news for this cone as these waves, particularly at their standing wave frequencies, give out energy long after the original impulse has gone, and badly colour the sound.

*Original Kevlar® Cone Impulse progression plot*
(Impulse Plot)
(Fig AI-1b)

- The Fast Compression Wave moves at different speeds in different directions
- The Cone appears to be acoustically square, even though physically round
- Reflections at the surround and / or chassis, do not occur at the same time in all directions, and:
- Reflected waves do not form the same standing waves in all radial directions
- If properly designed, standing waves in one direction cancel out those in another
- The Central (floppy) Dust Dome moves a great deal!
- After a time the surface of the cone appears to be more or less random in its behaviour

Note: Compression waves are much faster in Kevlar® than in Plastic, and there is hardly a trace of the bending waves that were present in the Plastic. Most of the energy is carried outwards by fast compression waves. Because they arrive at different times all around the circumference, any standing waves they form are not rotationally "coherent" and so do not add up in phase to pr

*Plastic, Original Kevlar®, and "Surroundless" Kevlar® Cones Compared* (Impulse Plot) (Figs 29a,b,c)

- AI-1a shows impulse moving from voice coil to surround on Plastic cone
- AI-1b shows impulse moving over Original Kevlar® Cone
- AI-1c shows impulse moving over surroundless Kevlar® Cone

Note Particularly

- Kevlar® is much faster than Plastic
- Surroundless Kevlar® is much faster than Kevlar with roll surround
- In both cases Kevlar® appears to be square acoustically, though round physically

The waves in the "surroundless" Kevlar® case are much faster than those in the original Kevlar® case we believe because the mass of the surround in the original case was sufficient to slow down the rising edge of the impulse response by simple $F= m * a$ considerations. The mass of the surround was holding back the movement of the cone and more particularly the outer regions of the cone were being restrained. The superior rise time exhibited by the "surroundless" Kevlar cone translates into a greatly extended frequency response which is actually usable up to between 7 and 8kHz, a very high frequency for such a large cone, and then because of the "symmetrical resonance cancellation effect", merely falls off smoothly above this frequency.

*Impulse Progression across a diameter "surroundless" Kevlar®*
(Fig 30)

This single slice impulse progression plot (Fig AI-2) shows:

- Lack of reflection of bending wave on LHS of the diameter
- Some reflection of the bending wave on the RHS of the diameter

The left hand side was half way between the bias and the warp direction, where the impedance is matched, whereas the right hand side is some way from the correctly matched condition showing some waves being reflected. Note also the very fast passage of the initial wave from the voice coil to the surround.

### Frequency whole cone plots

*Plastic Cone* (Frequency Plots)
(Fig AI-3)

- Whole Cone Frequency plots from 0.2kHz to 10.2kHz
- Many resonances are seen – all axisymmetric ie the same all the way round the cone

Note: The first resonance is seen at 210Hz – the lowest frequency displayed. This is where a half wavelength of the bending wave fits into the distance between the voice coil and the chassis, thus including both the surround and the cone. This is the fundamental of the surround resonance, which is thus the first harmonic of the standing bending wave. It is hardly ever noticed in frequency responses as its effect is usually minimal, even though the surround moves more than it ought to.

The next resonance above the fundamental appears to be only in the surround, when a circular dip is evident in the

After that the unit shows “four fold symmetry” this means that:
Sectors going up and down in the outer regions cancel out leaving:
Radiating central area decreasing in size with frequency, so that the directivity is largely constant above 3kHz because:
The radiating area is roughly halved by 4kHz and
The radiating area is roughly reduced to one quarter by 6kHz (Fig AI-4)

Theoretical plots are shown of the directivity of cones the size of the new midrange unit and ones having one half and one quarter the radiating area at 4 and 6kHz respectively. Measurements of the frequency responses at various degrees off axis, confirm that the output there is upheld approximately as predicted.

**A1-4**

## APPENDIX II – MATRIX™ CABINET CONSTRUCTION

The phenomenon of cabinet radiation has been recognised for as long as loudspeakers have been used in boxes. In theory, the function of the box is to act as a perfect obstruction to the acoustic field generated within it by the rear radiation from the drive units. Even vented enclosures rely on the panels containing, without deflection, the pressure element of the resonant action of the port.

Of course, real materials have finite loss and stiffness and hence will deflect in an acoustic field, and the problem has been to minimise this movement by judicious use of the available materials within the constraints of economics and ergonomics.

**AII-1**

In general, at low frequencies the stiffness of the walls dominates their behaviour, while at high frequencies it is their mass which rules. Between these two extremes they interact in a resonant manner which can grossly magnify and time smear the transmission at certain frequencies. This situation is rendered tolerable by resistive losses or damping.

In general one is trying to maximise all these variables, although at times it can make more sense to ensure that a resonance is outside the frequency band to be used than it is to keep it subdued with the use of mass or damping.

The stiffness of a panel for a given mass can be increased dramatically by curving it. Hence axially loaded tubes and spheres have long been recognised as the most efficient users of materials, though in our rectilinear society they have usually been relegated to more exotic designs.

The mass of panels can be increased simply through the use of dense material. Bricks, lead and sand layers all offer increasing attenuation with frequency, but these are all definitely for the DIY enthusiast.

In the real world, cabinets were made of wood with various degrees of panel bracing and damping, like bituminous mats and suchlike, which also helped increase the mass. By increasing both the mass and the stiffness, the lowest point in the curve corresponding to the minimum transmission loss may be brought up to reasonable levels. (Fig AII-1)

The upper picture shows the same speaker and cabinet side, but now there is a Matrix™ present. The effect of the Matrix™ is to virtually remove all traces of the cabinet vibration except immediately behind the speaker unit. The vibrations have been reduced by at least 45dB.

In this illustration, the cabinet was made of thick MDF material, (glued compressed sawdust), often used in speaker cabinets.

Points to note are
- A Matrix™ completely prevents the box sides vibrating where it connects to them
- A Matrix™ damps out any remaining vibrations in the much smaller unsupported regions
- Cabinet radiation is reduced by at least 45dB relative to no Matrix™ present

*Effect of Insufficient Transmission loss inside to outside* (Impulse Plot, Fig AII-3)

The plot shows the transmitted vibration of the side of a long tubular cabinet in response to an input impulse fed to a drive unit at the left hand side. So we have distance from left to right, and time moves away from us up the page.

Points to note are:
- The initial impulse moves from the speaker at the left, along the tube from left to right
- It is reflected at the right hand side and moves back again along the tube from right to left
- The wave speed can be determined from the acute angle of the initial movement to the x axis
- This is the speed of sound in air, not in the material of the box

This clearly shows that the box is not massive enough to stop the sound from leaking out through the material of the box itself. Note that a vibration in the chassis of the driving speaker can be seen at the left hand side.

**AII-3** Single Slice Impulse Progression Plot – Box Side

# APPENDIX III

## TAPERED TUBE THEORY

### Finite Element Analysis *Abstract*

The Finite Element Method was used to analyse the interior acoustic field of an inverted horn system. The finite element model was verified by comparing simulated and measured sound pressure level responses at an interior point. Contours of equal pressure phase were used to visualise the interior acoustic field. It is concluded that the frequency range over which the system can be used, is restricted by an upper frequency which is dependent on the diameter of the horn.

### Introduction

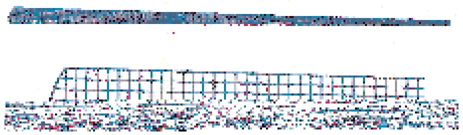
A common source of distortion in loudspeaker systems is internal acoustic resonances of the cabinet. High pressures can build up behind drivers at internal resonance frequencies of the cabinet, which affect the movement of the driver and thus colour the far-field sound. A solution to this problem is to use an inverted horn. A carefully designed inverted horn offers a smooth change in acoustic impedance which, when used in conjunction with an absorbent material, can result in a cabinet structure free of internal acoustic resonances.

In this paper, the results of Finite Element Analysis (FEA) of a prototype inverted horn designed for use in conjunction with an upper midrange dome are reported. Initial listening tests of the prototype revealed distortion occurring at approximately 10kHz. The Finite Element Method (FEM) was used to isolate the cause of this distortion.

The finite element model is described in '*The Finite Element Model*'. In '*Verification of the Finite Element Model'* the model is verified against the sound pressure level (spl) frequency response measured at an interior point. Finally, in '*Analysis of the Internal Pressure Field'* the interior sound field is analysed in more detail.

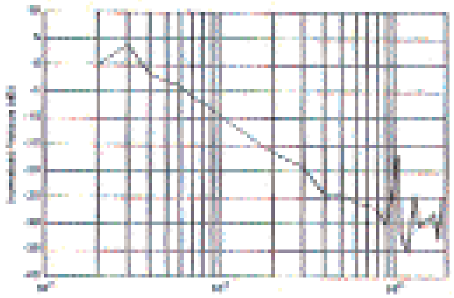
*The Finite Element Model*

The FEM is a mathematical technique that can be used to produce approximate solutions to partial differential equations. By utilising the FEM it is possible to carry out computer simulations of structural and acoustic systems. This paper is not intended to explain the FEM in detail. For detailed descriptions of the FEM applied to loudspeaker design see [Refs1+5], for example. The main point is that by applying the FEM, a virtual prototype can be constructed on a computer that can reflect the real world with sufficient accuracy to be useful in the design and analysis of loudspeaker systems. In this case a commer



**AIII-1** The Finite Element Model
Upper – the entire mode, Lower – close-up of the driver end

**a**
**AIII-1**



**AIII-1** Interior SPL responses **a** measurement and **b** simulation

The differences between the measurement and the simulation probably arise because of:

- Small differences in measurement position.
- The simulated response being taken at a point whereas the microphone essentially averages over an area.
- Simplification of the geometry in the FE model.
- Uncertainty as to the acoustic impedance of the wadding.

However, the correspondence between the simulated and measured spl response is generally good and it is therefore assumed that the whole of the interior acoustic field is modelled with sufficient accuracy.

*Analysis of the Internal Pressure Field*
To gain insight into the nature of the interior acoustic field, animations of equal pressure magnitude and equal pressure phase were made. Such animations are a powerful means of visualising the interior acoustic field. Contours of equal pressure phase especially are significant because wave fronts move in directions normal to these. Snap shots of equal-pressure phase animations are shown in Fig AIII-2.

At 5kHz it is clear that the inverted horn is behaving as expected – the direction of propagation is down the tube. However, at 10kHz there is clear evidence of a resonance across the diameter of the tube. This ties in well with the spl responses shown in Fig AIII-2 a-b, where a spike is visible at approximately 10kHz. At 11kHz, it is apparent that the main direction of propagation is down the horn but with a component across the diameter (this is very clear in animations).

## Concluding Discussion

The problem cross-diameter resonance could be removed or the effects reduced by using:

- a more effective wadding
- a tube placed inside the horn
- a flatter radiator which would not excite diameter modes so strongly.

Each of these cases were analysed using the FEM and all resulted in either removing or reducing the 10kHz spike. However, none offer a realistic solution to the problem.

It is clear from the results presented in this paper that inverted horns are only effective up to a certain frequency dependent upon its diameter at the throat. This is perhaps an obvious result but by using the FEM the effects can be quantified and clearly visualised.

*Sound Propagation down Nautilus™ Tubes* (Phases & Frequencies)

**a** Top plot shows a plane wave moving smoothly down a Nautilus™ tube at low frequencies.
**b** Middle Plot shows the wave at the cut-on frequency of the first-order mode of propagation. This occurs as a resonance across the tube width.
**c** Bottom plot shows the propagation above the cut-on frequency. Energy then moves down the tube as a combination of plane waves and first order modes.

Note: all pipes and ducts will allow plane-only waves to pass down them below a certain frequency that depends on their cross sectional dimensions. Above a first critical cut-on frequency waves can also propagate in a zig zag fashion along the tube. The angle of the zig and zag changes with frequency and is at right angles to the length of the tube at the cut-on frequency – which therefore shows up as a cross mode. Higher-order modes of propagation also have their own cut-on frequencies, which will also show up as cross resonances at higher and higher frequencies. For best effect therefore, Nautilus™ tubes can only be used up to the cut-on frequency of their first higher-order mode. Ref: Book ‘Mechanical Waveguides’ by Martin Redwood.

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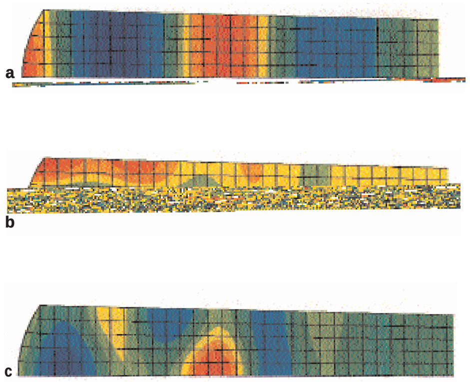

**AIII-2** Simulated results showing contours of equal pressure phase **a** 5kHz, **b** 10kHz and **c** 11kHz

## APPENDIX IV

## FINITE ELEMENT ANALYSIS

### Introduction

Much work at B&W over the years has resulted in proprietary Finite Element and Boundary Element code capable of accurately predicting the vibration and acoustic behaviour of axisymmetrical shapes using Finite and Boundary Element Analysis. Papers listed (refs) include several on this topic. B&W proprietary code runs at more than 10 times the speed of any commercially available package and allows in-house optimisation packages based on “simulated annealing” to find the global minimum of any target function we may like to specify. The result of this is that a computer may be left to search through the whole relevant design space to find the best model that will fit our requirements – and it will not be trapped in any local minima along the way.

When non-axisymmetric modelling is needed, commercial Finite Element packages have to be used and one of these, PAFEC, allowed the modelling of the total acoustics of normal Nautilus™ rearward inverted horns, though not the coupling of a lumped parameter speaker model at the near end. The tube was therefore excited with an “ideal” forced diaphragm for this exercise. As expected, this shows up the onset of the first higher order cross mode of propagation as a resonance across the mouth of the horn (ie where the speaker is situated). This graphically illustrates that rearward Nautilus™ horns may not be used on their own above this cut-on frequency, as this transverse mode is clearly audible through the speaker diaphragm.

The following report from Gary Geaves covers the analysis of this phenomenon:

### B&W Loudspeakers Ltd and Computer Simulation

Computer simulation based on the Finite Element and Boundary Element methods has been widely exploited in many diverse scientific and engineering applications. The Finite Element Method was developed in the 1950s to aid in the design of aircraft structures. Since then it has been applied to structural, thermal, electromagnetic, fluid flow and acoustic problems. In many industries, such as the automotive, it has been long regarded as an essential design tool. However, it is only relatively recently that sufficient computer power has become readily available and the underlying mathematical techniques sophisticated enough to be of use in the design of loudspeakers.

Engineers at B&W were quick to spot the potential of computer simulation in the design of loudspeakers, first becoming involved through collaborations with academic institutes in the mid 1980s. At that time, if one wanted to carry out simulation of an acoustic system, it was necessary to develop and code the algorithms from scratch. For this reason, B&W has proprietary code, written in the Fortran programming language, to solve a specific class of problem. This code is used routinely and is being constantly enhanced. It has also been used as the basis for an optimisation system that will automatically select designs fulfilling specified design criteria.

Recently, especially in the last five years, commercial, off the shelf systems have become available that allow simulation of acoustic systems to be per[illegible]

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### Phase animated – single frequency – full-surface scan

The full-surface phase-sensitive detection method is used for this type of plot except that, instead of just one whole surface scan, a set of up to 20 surface scans are carried out, each one being at a different phase though the vibration cycle. When these 20 pictures are placed in the computer's memory, a second programme allows all twenty pictures to be repeatedly mapped onto the screen. This gives the impression of animation and can often show up features in a speaker's response not clearly visible from a single frozen-phase whole-cone scan. For IBM PCs these can be produced as ".AVI" files which may be played with the standard Windows™ media viewer programme.

*Phase Animated Single Frequency Plot* (20 Phases) Fig AV-3

- Complete single-frequency phase-sensitive plot over whole cone
- A bell mode is evident, giving peaks and dips around cone's circumference
- A resonance in the surround can clearly be seen – it is the first harmonic
- The surround pulls tight at top dead centre (see single slice at the top left)
- The picture shown here is from top dead centre

Note: The bell mode has an equal number of sectors going upwards and downwards. These are also of equal amplitude and therefore their radiation cancels out in the near field (it's an "acoustically fast" multipole source). The surround resonance is not cancelled out by anything and is responsible for a clearly be seen – [illegible]

### Phase Animated Frequency Slice Plots (Fig AV-4)

Just as with the slice plot above, a complete set of scans is done from a low frequency to a high frequency at each of 20 different phases. The resulting 20 plots are then animated, revealing each slice's behaviour as it moves though a complete vibration cycle. This rather curious "frequency normalised" phase animated frequency slice plot shows the same 20 phases for each frequency, so the animation proceeds at the same rate for 20kHz as it would for 200Hz. Another form of plot, as yet to be produced, would cycle though the phases at 20kHz at 100 times the rate that they are cycled at 200Hz. It is doubtful though whether such a plot would be of any use. The frequency-normalised phase-animated slice plot gives the impression that energy passes down the plot from low frequencies to high frequencies, but this is merely an artefact of the normalisation.

Plots such as these show in graphic detail phenomena such as the progression of energy from the voice coil to the surround at high frequencies, just like waves moving down a length of rope being shaken up and down at one end. Also often seen is the surround lagging behind the movement of the otherwise piston-like cone by 90º.

*Phase Animated Frequency "Slices"* (20 Phases) (Fig AV-4)

- Rear Slice is a scan across the middle of the cone at 0.5kHz
- Front Slice is a scan across the middle of the cone at 5.5kHz
- Each frame is at a different phase through a complete cycle at each slice's frequency
- This is a very bad cone, showing major resonances and poor surround behaviour
- The single frame from the sequence shown here illustrates the surround phase lag at the rear

Note: The slice at the front, at 5.5kHz, is just like a rope being waved at one end. No sound will be radiated at this frequency. Even the slice at the back, at 0.5kHz, shows that the surround lags behind the cone (otherwise behaving like a piston) by 90º. Thus the surround radiation will cancel and reinforce the cone sound differently depending on the direction. On axis there will be little effect, but the directional pattern will suffer peaks and dips as a result. The major resonances produce peaks and dips in the speaker's response in all directions.

### Impulse Progression Plots – in cones and in the air – slices or full cone

The latest technique in the formidable armoury of laser-based measurement techniques available to B&W engineers is called the Impulse Progression Plot.

In this case, the laser beam is pointed at a position on the cone and the speaker is fed with an impulse, rather than either a single frequency or a sequence of [illegible] impulse response of the point is stored in the computer and the beam is moved on to the next point, where its impulse response is translated into digits.

For the single slice impulse progression plot, just a single line of impulse responses is used. For the whole cone case obviously, impulse responses from the whole cone surface have to be translated for processing later.

With a single line of impulses, a plot is produced across the whole diameter for each time interval of the sampling of the individual impulse responses. Each succeeding time interval may be produced as a 3-D plot, with time equals zero placed at any edge of the page (usually at the left hand side). The resulting cone behaviour is then displayed in 3-D as a time history from left to right (or whatever).

Alternatively, the single line may be displayed on the computer as a movie, and the line then appears to waggle up and down as the impulse progresses back and forth along it. However, perhaps the most useful presentation technique for the single slice impulse progression plot is as a coloured contour plot, with time equals zero at the left hand side – time therefore progresses from left to right, with the voice coil in the middle and the surround at top and bottom. An example of this is shown in figure AV-5.

This sort of presentation immediately reveals that there are several different types of wave motion conveying energy from the voice coil to the surround and back again. The most significant of these are bending waves and compression waves, the latter travelling much more quickly than the former. Figure AV-6 shows the impulse coming in at the voice coil in the centre. The cone begins to follow it and the wave progresses outwards in both directions to strike the surround near the edges of the picture. This looks very much like ripples produced when a stone is dropped into a round pond.

A computer animated version of this picture shows in graphic detail how much of the incoming bending wave is taken into the surround and how much is reflected back down into the cone again to form standing waves or resonances. The impulse may also be seen moving about in the surround itself, all the while being absorbed and reflected during its travels. The cone can clearly be seen to behave like a transmission line for bending waves (and for other types of waves as well) and for best effect should be terminated in the characteristic impedance of that line at both ends. This will ultimately produce minimum reflections and maximum absorption and consequently fewer resonances and a cleaner sound output.

## Generalisations

As with all the above single slice types of plot, this single slice impulse progression plot is especially applicable to axisymmetrical cone structures.

For materials such as woven Kevlar®, the whole cone impulse progression plot has to be used. In this case, a complete picture of the whole cone is built up from each of the sampled individual time elements making up the impulse responses at each point on the cone. These pictures are cycled from either the hard disc or the memory of the computer onto the screen, showing graphically an animation of the progression of the impulse across the whole of the cone surface.

**AV-5** Wavefront Arrival Plot – Sound in the Air

**AV-6** Impulse Progression Plot – Cone Diameter

## Plots of the motion of the air motion itself

As described in the paper "Laser Techniques in Loudspeaker Design including the Impulse Progression Plot", B&W has a Laser Doppler Velocimetric technique for observing the passage of waves across the surface of a speaker cone. As further shown in the Paper "New Pipe and Horn Modelling", this technique may be extended to measure air motion in order to discover which parts of the speaker cone do the radiating and which parts of the speaker box allow waves to be diffracted, so spoiling the resulting sound. The technique involves placing a very light, highly stretched clingfilm diaphragm, lightly dusted with talcum powder, in front of the driver. Although this diaphragm is like gossamer and is totally acoustically transparent, it does move with the passage of any sound wave, behaving almost like part of the air up to supersonic frequencies. Since it moves with the sound it may be observed with the Laser Doppler velocimeter, which therefore detects the movement of the air itself. (Fig AV-6)

This technique may be used in a number of ways. The most obvious is to scan a whole diaphragm placed in front of a cone or speaker box. This allows us to observe the progression of the impulse across the air in front of the cone and across the surface of the box. The second way is to place the diaphragm in a succession of positions further and further away from the speaker or box and measure either a slice across the diaphragm, or indeed the whole diaphragm at each position. Computer processing then allows the passage of the impulse in the air to be viewed as it passes through each successive diaphragm, either as a succession of "stills" or as a computer animated movie. This is very useful for observing the transitions from near field behaviour close to the driver or speaker box to far field behaviour, which is what is usually perceived by the listener, and to pin point sources of diffraction and radiation within the total speaker system.

The passage of an impulse though a single diaphragm may be displayed as a 3-D plot, rather like the slice plot for displaying the behaviour of a single slice across a speaker diaphragm at different frequencies. In this case, the first arrival is plotted at the right hand side and subsequent arrivals are displayed from right to left. We thus see graphically with this "wavefront progression plot" how energy comes along well after the original impulse has passed that point in space.

When observing the differences between the impulse behaviour of axisymmetric cones such as those made from plastic, with non axisymmetric cones made from woven Kevlar® fibres, the difference is striking. The sound energy radiated by the axisymmetric cone consists of an initial wavefront, which largely represents the music, followed by a series of other waves, which are not the same in all directions, representing the coloration of the cone and caused by the waves bounding backwards and forwards across the cone. Measuring the behaviour of the air can also be used to illustrate how cabinet edges really do produce copies of the original sound, but often out of phase with the original and delayed by the time it took for the sound to get from the driver to the diffracting sharp edge. (Figs AV-7 and 8)

**AV-7** Phase Sensitive Frequency

**AV-8** Phase Sensitive Frequency

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B&W Loudspeakers Ltd, Meadow Road, Worthing, BN11 2RX, England.

B&W Loudspeakers (UK) Ltd, Tel: +44 1903 750750, Email: uksales@bwspeakers.com
B&W Loudspeakers of America, Tel: +1 978 664 2870, Email: marketing@bwaudio.com
B&W Loudspeakers (Asia) Ltd, Tel: +852 2 790 8903, Email: bwahome@bwspeakerasia.com.hk
**www.bwspeakers.com**

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