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## Design of a Coincident-Source Driver Array with Radial Channel Phase-Plug and Novel Rigid Body Diaphragms

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### ABSTRACT

The simple source characteristics that coincident-source driver arrays promise are an attractive design goal but many engineering obstacles must be overcome to avoid undesirable complex behaviour. This paper outlines an innovative design approach which achieves simple source behaviour over several octaves and avoids the complex acoustical and vibrational behaviour found in traditional drivers.

The high frequency section of the driver combines techniques for optimising the response introduced by Dodd [1] and the radial channel phase-plug design, introduced by the authors [2]. The midrange unit uses a cone with novel geometry allowing it to move as a rigid body to over an octave above the crossover frequency. The resulting driver and its measured behaviour is described in the light of some possible alternative approaches.

## 1. INTRODUCTION

Coincident-source driver arrays have a high frequency driver positioned close to the apex of a cone midrange unit. This allows the possibility of point source characteristics rather than the more complex behaviour produced by conventional systems with spatially separated drivers. Not only can the effects of interference be avoided but also the directivity of the drivers may be matched at the crossover frequency to avoid anomalies in the energy response. A well designed coincident-source driver array will behave almost as a point source albeit with directivity smoothly narrowing with increasing frequency.

However, coincident-source driver arrays present numerous engineering challenges that must be overcome to avoid undesirable behaviour. The close proximity of the drivers restricts the available space and the waveguide surface must also function as a midrange diaphragm. Furthermore, the drivers may have spurious diaphragm resonances which will result in aberrations in the frequency response and dispersion. Fincham [3] was able to make a practical coincident-source driver array due to the compact dimensions of Neodymium Iron Boron (NdFeB) magnet assemblies. The initial driver used vacuum formed polymer diaphragms, using Supranyl for the high frequency dome and polypropylene for the midrange cone. Both of these diaphragms behaved in a non-rigid manner over significant parts of the working range and relied on high internal losses to ameliorate response aberrations. Later work by Anthony et al [4] resulted in a high frequency driver that behaved as a rigid body throughout the audio band. However, simply avoiding diaphragm resonances is not enough on its own to assure good audio performance and systems using this driver required an additional driver to extend the response to the very high frequencies required in the market. More recently work by Dodd [1], in which the acoustic performance is considered, showed that the shape of a rigid radiating dome must be closely matched to the waveguide geometry to avoid on-axis response irregularities and spatial response variation. A new methodology for annular channel phase-plug design developed by the authors [5] for compression drivers was then applied to a radial channel phase-plug situated in the geometry developed in [1].

This paper describes the practical implementation of a high frequency driver using the combined techniques

for optimising the response introduced by Dodd [1] and the radial channel phase-plug design, as introduced by the authors [2]. The design is developed into one that achieves higher performance than the original design in [2] and may still be moulded integrally with the static part of the waveguide.

A novel geometry for the midrange cone allowing it to behave as a rigid body to more than one octave above crossover frequency is then introduced. This geometry also has the correct shape required for it to function as a waveguide for the high frequency driver. Particular attention is paid to the driver directivity. The cone diameter and waveguide shape allow the midrange driver directivity to match the high frequency directivity giving a smooth energy response. The resulting driver and its measured behaviour is described in the light of possible alternative approaches.

Due to the limitations of space and time this paper focusses on two main areas. Firstly, avoiding diaphragm resonances and secondly, producing point source-like acoustic characteristics from a coincident-source driver array. Many other interesting aspects of driver design have thus been omitted from this paper.

## 2. HIGH FREQUENCY TRANSDUCER

The high frequency transducer must reproduce the frequency range from 2.2kHz to beyond the audible range with sufficient efficiency to match that of the midrange driver. The high frequency transducer should have a smooth response allowing a simple passive filter to provide the necessary bandwidth limiting and any equalisation. The spatial dispersion should decrease smoothly with increasing frequency and not exhibit 'beaming', 'lobing' or other anomalies. Furthermore the driver must fit within the physical confines of the midrange driver.

### 2.1. Rigid Diaphragm

The acoustical requirement for diaphragm shape outlined in [1] does not result in sufficiently high geometric stiffness – such a 25mm diaphragm is unable to work as a rigid body up to the highest frequencies of the audio band. Since the shape is a major factor in determining diaphragm stiffness it was decided to introduce a titanium former with a top part that has a similar shape to the diaphragm used by Anthony [4]. This former contacts the diaphragm in two different

positions and allows a diaphragm with the correct acoustical shape to behave as a rigid body to higher frequencies. This novel geometry may be seen in figures 1 and 2.

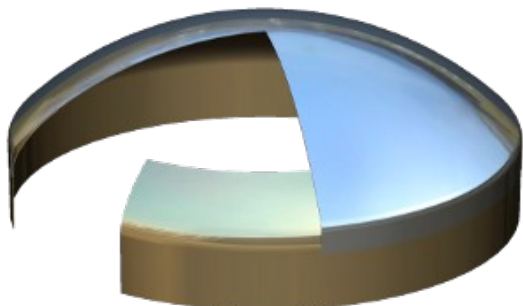


Figure 1. Cut-away dome with extended former exposed.

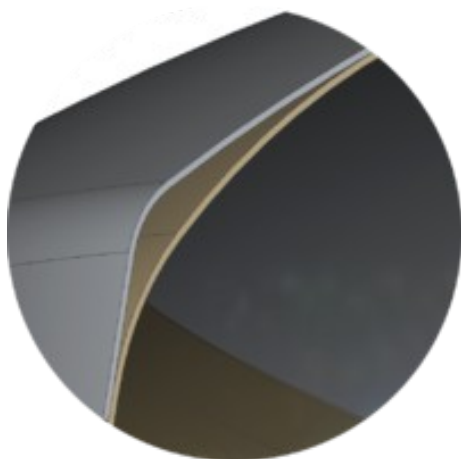


Figure 2. Detail of dome and extended former.

Table 1 shows the frequencies at which the first mode occurs with an unsupported dome and with the extended former supporting the dome. The first axial dome mode is increased dramatically from 21,918Hz to 33,799 Hz ensuring rigid piston behaviour to well above the audio frequency range.

	unsupported	with stiffener
Mode 1	21,918 Hz	33,799 Hz (+54%)

Table 1: Comparison of breakup mode of dome with and without extended-former stiffener.

The motion of the surround has also been considered: both geometry and material have been chosen after simulation with coupled Finite Element Method to Boundary Element Method models (FEM/BEM) to avoid resonances in the pass band.

## 2.2. Radial Channel phase-plug

A radial phase-plug, designed according to the methodology in [2], transforms the acoustical particle motion from axial diaphragm motion to a close approximation of a pulsating sphere at the end of the plug. The waveguide walls are correctly shaped to allow spherical wave propagation resulting in wider dispersion and greater output than the original, uncovered dome.

The radial channel phase-plug approach outlined in [2] leads to a geometry where ideally all channels become infinitely narrow in the central region of the plug. To allow the design to be injection moulded it is necessary to truncate the plug in the axial direction and maintain a sensible minimum wall thickness. Additionally the width of the phase-plug channels cannot be so narrow that the strength of the tool is compromised. The initial practical version of radial slot phase-plug introduced in [2] is shown in Figure 3.

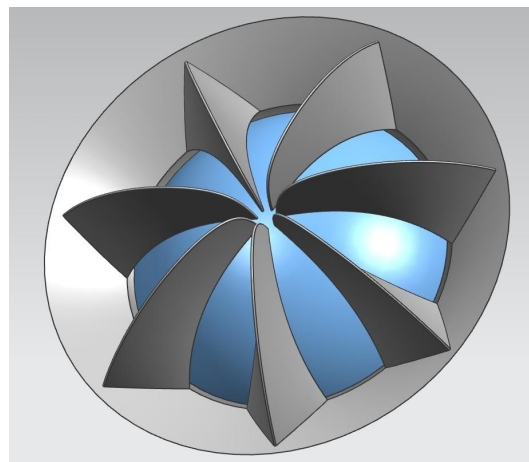


Figure 3. Early radial phase-plug with low compression ratio and 19mm diaphragm as described in [2].

This phase-plug was designed for a 19mm diaphragm and was required to have a response only extending up to 20kHz allowing a simple design with seven segments to give the moderate performance improvement shown in Figure 4.

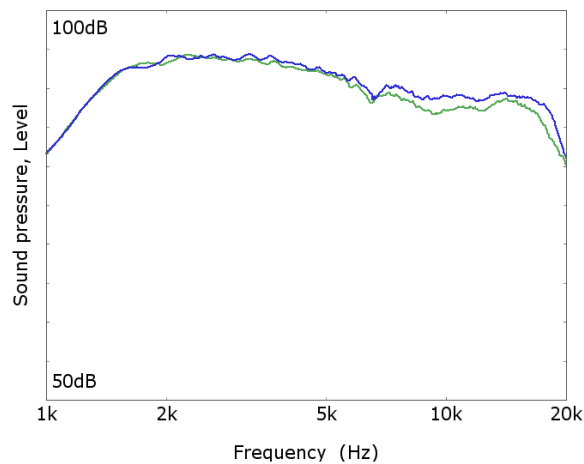


Figure 4. Response of driver with phase-plug shown in Figure 3(Blue) and without phase-plug (green)

### 2.2.1. Improved Phase-Plug Design

The new design had to satisfy more stringent requirements. The frequency range must extend well beyond 20kHz even though the diaphragm is larger at 25mm outside diameter. To improve the maximum sound pressure output and avoid thermal compression it was also desired to gain 4dB in sound pressure level at 20kHz, the least sensitive part of the response, using the compression-driver effect of the phase-plug.

The requirement for a greater sensitivity increase leads to a phase-plug which must cover more of the dome. The increased size and extended high frequency range revealed the presence of circumferential acoustical modes which short circuit the acoustic output from the dome causing response dips of several decibels. Using FEM/BEM simulations it was found that these circumferential modes could be avoided in the working range of the driver by increasing the number of segments in the phase-plug to twelve. However, with twelve segments, the resulting thin wall sections in the central part of the plug along with the thin air channels proved impractical for manufacture.

After several months, with the assistance of numerous iterations of parametrised 3D CAD driven FEM/BEM simulations, a successful approach was found: at the centre of the phase-plug the number of channels is reduced from twelve to three. This is sufficient to avoid the circumferential acoustical modes and is also practical to manufacture as a single part using conventional injection moulding techniques. The

distinctive new design is shown in Figure 5 and Figure 6. The area weighting design rule outlined in [2] is still obeyed through very careful construction of this new geometry.



Figure 5. Plan view of new high compression ratio phase-plug for the 25mm diameter diaphragm

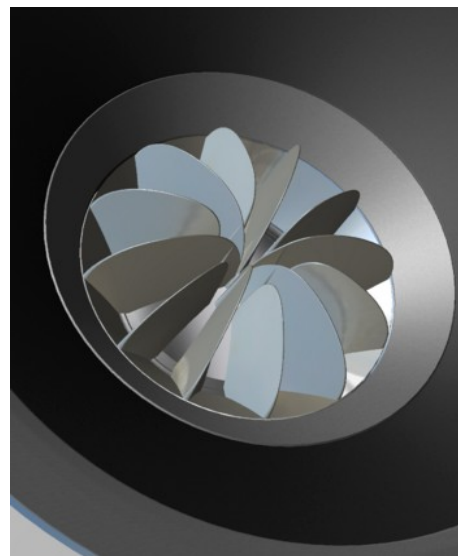


Figure 6. Isometric view of new high compression ratio phase-plug for the 25mm diameter diaphragm

The resulting performance improvement is quite significant. Figure 7 shows the one meter axial frequency response of the new high frequency driver with and without the radial channel phase-plug. It may

be observed that in addition to the increase in the sensitivity of the tweeter, the smoothness of the response has also been improved.

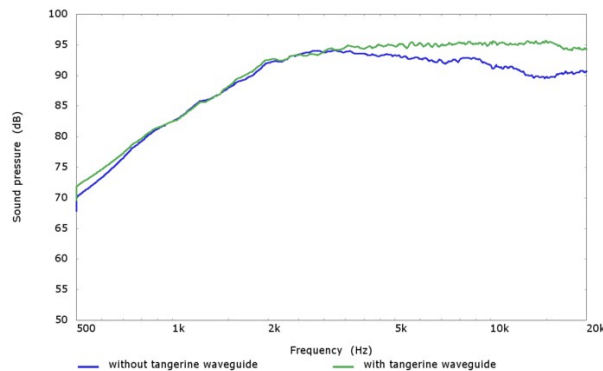


Figure 7.  $2\pi$  response of new driver with (green) and without (blue) radial channel phase-plug fitted.

### 3. MID FREQUENCY TRANSDUCER

The Mid-Frequency transducer's input has high and low-pass filters applied at 350Hz and 2.2kHz. However, the finite passive filter slopes require a response free from large peaks well above 2.2kHz in order to avoid anomalies in the summed system response. In addition the diaphragm of the midrange driver has its shape predetermined by its function as a waveguide for the high frequency driver. The midrange driver must also leave a suitable space to accommodate the high frequency driver.

To avoid response and dispersion irregularities the authors adopted a design goal that the diaphragm should not exhibit structural resonances until at least an octave above the upper crossover frequency. As we shall see, achieving this ideal on a midrange driver is particularly difficult.

#### 3.1. Rigid Diaphragm

Loudspeakers often use a radiating membrane of conical shape. The conical geometry is inherently stiff since axisymmetric external forces are transformed into tensional stresses in the material. Even a very thin material, which will have little resistance to bending, has significant stiffness in a conical form. However, at sufficiently high frequencies the conical diaphragm will suffer from structural resonances. When such designs are used as midrange drivers these resonances often lie within the working band.

The most common approach to midrange driver cone design is to accept that there will be resonances in the pass band and to control their effect on the response by the use of curved cone profiles and well damped materials. The number of resonances in the pass band is often increased by this strategy but it is commonly argued that the audibility of individual resonances is reduced if the overall spectral density of resonances is increased. However, the effect of the resonances is still evident in the driver response, particularly the polar response, and it was the aim of the authors to avoid this compromise in performance.

Another approach is to make the cone from a metal such as titanium or aluminium so that it has a first breakup mode above the cut-off frequency of the low pass filter. However, the low inherent mechanical damping of metals results in severe resonances. The magnitude of the resulting response peak is sufficiently large to be evident in the system response even if breakup occurs above the upper crossover frequency. Consequently the use of a metal cone was also rejected.

An extensive search for suitable alternative materials yielded Liquid Crystal Polymer, or LCP, a partially crystalline aromatic polymer. When loaded with Carbon Fibre a density of  $1.5 \frac{g}{cm^3}$  and Young's modulus of 25GPa may be achieved. This high Young's modulus and low density push structural resonances much higher in frequency compared to other plastics while the high levels of internal damping ensure resonances do not cause the substantial peaks in the response found in metal cones. From a practical point of view LCP is also well suited to injection moulding and can achieve the thin wall thicknesses required by loudspeaker cones.

Figure 8 shows the simulated pressure response of a driver with a 93mm diameter LCP cone, radiating into a semi-infinite acoustical region equivalent to a  $2\pi$  baffle. The pressure is plotted for 46 positions at 1m from the loudspeaker and 2 degree angular increments. This simulation was performed using PAFEC-FE [6] providing a fully coupled vibro-acoustical FEM and BEM sinusoidal solution on the meshed geometry under consideration. Even with this exceptionally rigid material, above approximately 1.5kHz the pressure response of the loudspeaker becomes irregular due to resonances resulting from non-rigid behaviour of the cone. In particular, it is interesting to note that while the response on axis is relatively smooth the response at other angles is extremely irregular. The undesirable nature of non-rigid behaviour is clearly illustrated by

both the irregular axial response and directivity of the loudspeaker.

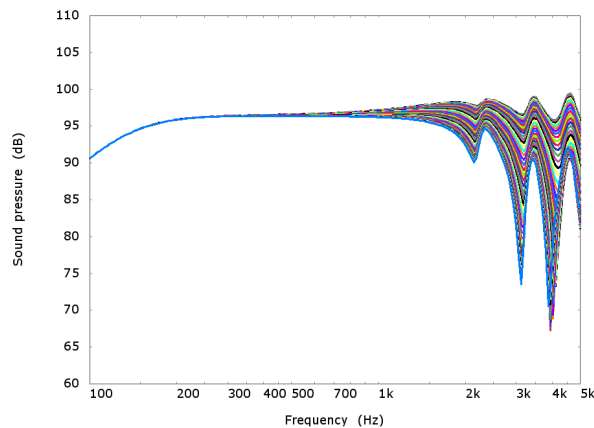


Figure 8. 93mm LCP cone loudspeaker 1m polar response at 2 degree angular increments. The upper curve is axial, the lowest is the 90degree response.

A further improvement in performance is required to achieve the design goal of a rigid piston driver. One interesting method for extending the bandwidth of rigidity in a loudspeaker diaphragm is to drive the diaphragm at a resonant node [7].

Figure 9 shows the displacement of the cone for the first mode at 2kHz derived from the same BEM/FEM simulations that was used to calculate the response in figure 8. The displaced diaphragm (solid red) is superimposed on the rest position of the diaphragm (outline). Where these displaced and rest geometries coincide the diaphragm is stationary, such positions are commonly called nodes of vibration. If we increase our voice coil diameter so that it attaches to the cone at this nodal position we can prevent this particular resonant mode from being excited.

To investigate this idea further a cone loudspeaker using this new voice coil diameter was modelled using the same process. The resulting 1m frequency responses at the same angular increments are shown in Figure 10. The irregularities now begin at a higher frequency, approximately 3.5kHz, because the first vibrational mode is prevented from being excited. Unfortunately, applied to a cone shaped diaphragm, this interesting technique has limited benefit since the modes are closely spaced in frequency. While we have managed to somewhat increase the bandwidth where the cone is behaving rigidly it is not sufficient to meet our design goal.

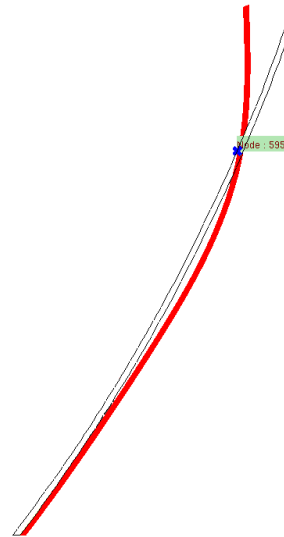


Figure 9. FEM derived displacement showing the nodal position of the cone at the first resonant frequency.

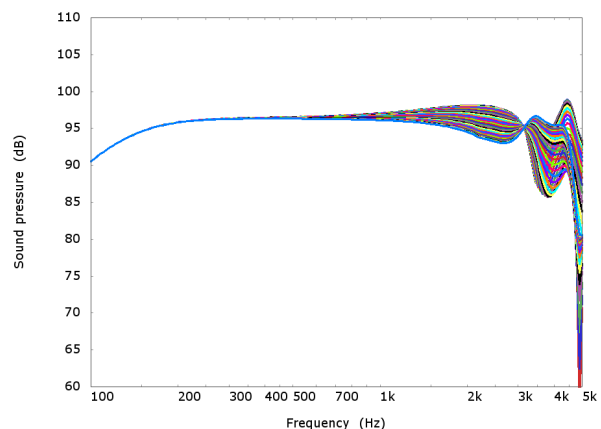


Figure 10. Cone loudspeaker driven at node of first mode of vibration, 1m polar response at 2 degree angular increments.

The authors found that by adding carefully positioned ribs to the rear of the cone, as depicted in figure 11, it is possible to dramatically increase the improvement given by nodal drive. Firstly, the mode frequencies are increased in frequency. Secondly, the nodal position of the first resonance is adjusted so that it is at a more convenient smaller coil diameter than the cone without the ribs. Figure 12 shows the displacement of the new ribbed cone for the first mode at 2.995kHz and the corresponding nodal position.

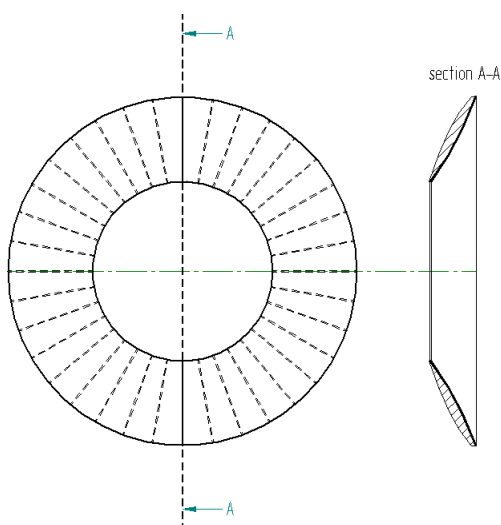


Figure 11. Loudspeaker cone with reinforcing ribs.

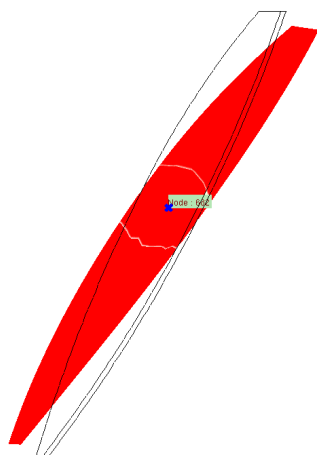


Figure 12. FEA Modal analysis to determine the nodal position of the ribbed cone at first resonant frequency.

Table 2 shows the first two mode frequencies for the conventional cone (unsupported) and the ribbed cone derived from the FEM results.

	Unsupported	With Ribs
Mode 1	2268Hz	2995 (+32%)
Mode 2	3414Hz	6069Hz (+77%)

Table 2: Comparison of modal frequencies of supported and unsupported cone.

The resonant modes have all shifted up in frequency, but interestingly, the second mode of the cone has shifted much more than the first mode. This is extremely useful: by driving the cone at the nodal position of the first resonance we can avoid any modal excitation until 6kHz. The simulated frequency response of this ribbed cone, driven at the first node of the first resonance is shown in figure 13. The response is remarkably smooth and well controlled compared to the starting point of a conventional cone as shown in figure 8. The midrange driver was designed using this arrangement, the cone and voice coil are illustrated in figure 14.

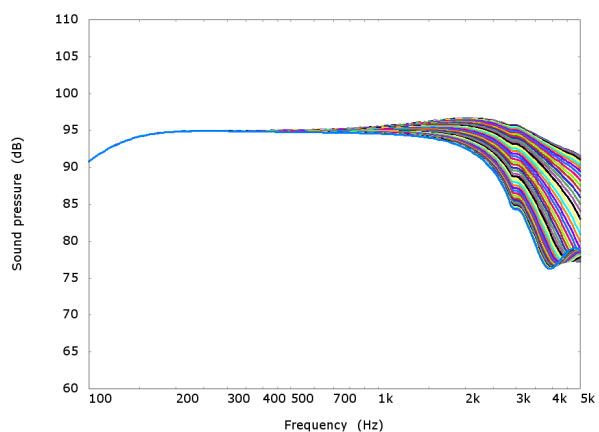


Figure 13. Ribbed cone loudspeaker driven at node of first resonance, 1m polar response at 2 degree angular increments.

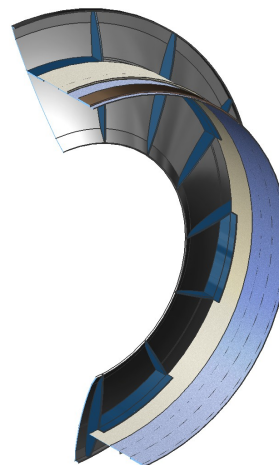


Figure 14. Isometric sectional view of modelled midrange cone.

The measured response of the midrange driver mounted in a cabinet is shown in figure 15. The measurement was performed using a 2.83V RMS logarithmic chirp stimulus captured at 2m on axis with the driver windowed at 14ms, just before the first room reflection, the curve resolution is 48 points per octave it is not smoothed.

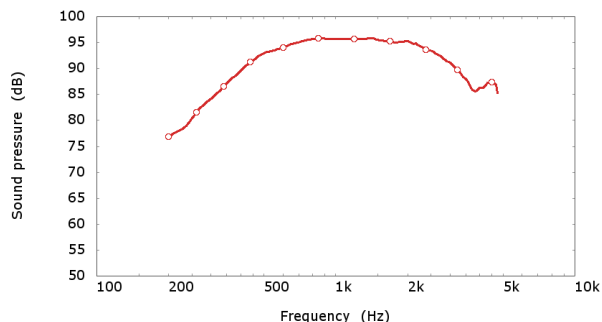


Figure 15. In cabinet measurement of midrange driver frequency response.

Figures 16 and 17 show waterfall plots calculated from  $2\pi$  baffled 1m axial impulse response measurements of a conventional midrange driver, operating in breakup at the top end of the bandwidth shown, and the midrange driver described in the paper respectively. The waterfalls were calculated with a 256 sample hamming window and an overlap of 250 samples, the impulse responses were captured using a logarithmic sweep method at a sample rate of 80kHz.

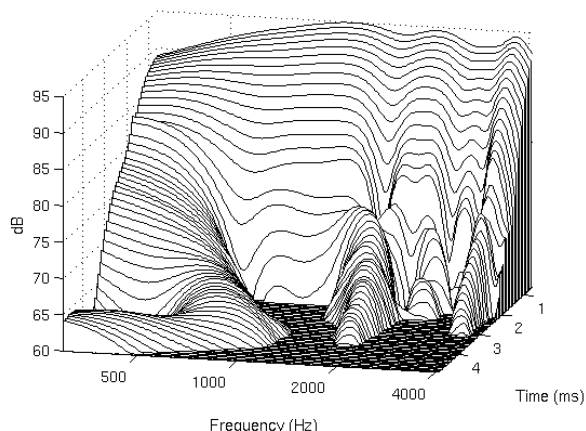


Figure 16. Waterfall plot of a conventional midrange driver operating in breakup.

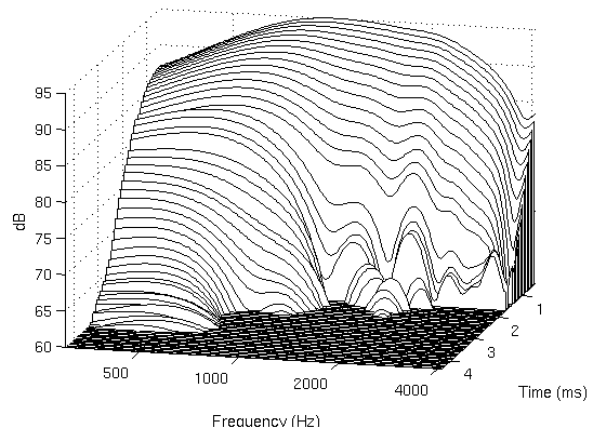


Figure 17. Waterfall plot of new midrange driver.

Comparison of the two waterfalls reveals that the new midrange driver decays more quickly particularly in the upper half of the displayed bandwidth and is notably free from resonant tails.

#### 4. COINCIDENT-SOURCE DRIVER ARRAY

The complete driver is illustrated in Figure 18. Extensive use of numerical simulations was made to optimise magnetic and vibro-acoustical linear and non-linear performance.

The large coil diameter of the midrange driver has allowed a substantial NdFeB ring magnet to be used for the high frequency driver motor system which has a large vent hole to avoid excessive sound pressure levels in the cavity behind the dome. The duct leading away from the vent is damped to avoid standing waves. A plastic film suspension allows adequate excursion while avoiding spurious resonances in the audible frequency range.

The midrange driver itself uses 14 NdFeB cylindrical magnets to achieve sufficient flux for an under-hung 78mm diameter voice coil. Inner and outer foam surrounds allow axial movement of the diaphragm while providing a seal to prevent the rear of the cone radiating and to provide a smooth surface for the waveguide. A half roll polymer suspension provides a linear restoring force.

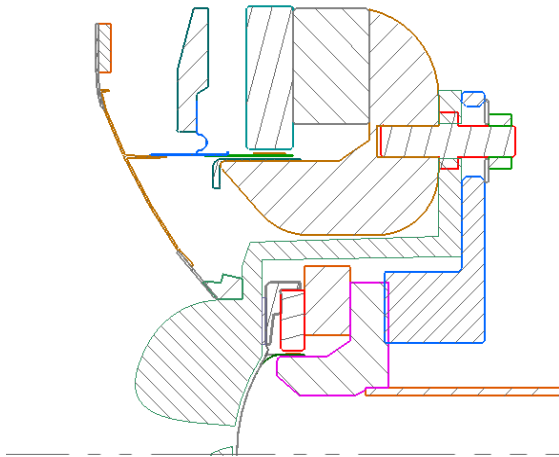


Figure 18. Half-sectional drawing of the complete driver

## 5. APPLICATION IN SYSTEM

To complement the point source characteristics of this new coincident-source driver array a system was designed with an array of four 10" low frequency drivers positioned with the apparent acoustic source coincident with the axis of the coincident-source driver array. The spacing of the drivers allows control of the low frequency directivity. In this case the spacing results in the system spatial dispersion smoothly decreasing with increasing frequency.

The array of drivers also allows force cancelling and, when combined with the curved enclosure front, produces minimal diffraction. In the area where the coincident-source driver array is positioned the enclosure front extends the waveguide formed by the cone. Great care has been taken to avoid discontinuities between the surfaces forming the waveguide.

## 6. COINCIDENT-SOURCE DRIVER ARRAY PERFORMANCE

The curves in figure 19 show the combined mid and high frequency driver response on-axis and at 20 degree increments off-axis. There is little evidence of diffraction apart from a slight ripple in the axial response. The separation of the off-axis responses increases smoothly with increasing frequencies to beyond 20kHz. The response varies only slightly with increasing angle, giving a balance that remains

acceptable over a wide listening area. The lack of mechanical resonances and correspondingly smooth frequency response also produces a rapid decay in the time domain.

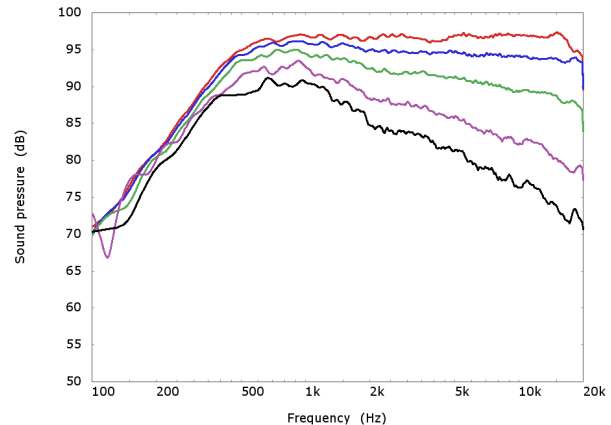


Figure 19. Measured response of new coincident-source driver array in prototype enclosure, on-axis and at 20 degree increments horizontally off-axis.

## 7. DISCUSSION

The subjective performance of loudspeakers is difficult to evaluate in a rigorous manner. None the less the authors felt some comment of these findings would at worst create an interesting debate.

Gratifyingly, it has been found that there is a lack of subjective colouration combined with excellent intelligibility. The stereo imaging is also exceptionally well focussed due to the spatially coherent sound field. Perhaps more surprising in view of this coherent behaviour is the ambience revealed in recordings.

## 8. CONCLUSION

A new high frequency driver with optimally shaped diaphragm, reinforced by a carefully designed titanium former in a wave-guide incorporating an area weighted radial slot phase-plug has been described.

In addition a highly innovative midrange driver with ribbed LCP cone and nodal drive has been introduced.

Both of these drivers have diaphragms which do not suffer from resonances until frequencies much higher than their working ranges.

The integration of these resonance free drivers into a coincident-source driver array achieves point-source-like characteristics. The frequency response is smooth and spatial dispersion progressively decreases with increasing frequency. These performance characteristics are maintained over a bandwidth of several octaves using only a simple passive crossover network. A suitable array of low frequency drivers can extend this behaviour over the full audio frequency range.

During the development of this system there was much debate on whether such a technologically purist approach would produce a loudspeaker with sonically

pleasing characteristics. Having completed the design process it is evident to the authors that a coherent loudspeaker with point source like characteristics is a target well worth pursuing.

## 9. ACKNOWLEDGEMENTS

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