PERFORMANCE PREDICTION OF A VOLUMETRIC ARRAY OF FREE FLOODED RING PROJECTORS

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1. INTRODUCTION

There is interest in developing *directional* low frequency active sonar arrays for various applications. Employing ring transducers as sources in compact directional arrays represents a considerable technical challenge. The performance of arrays of rings is difficult to predict as the behaviour of the individual projectors is not easy to characterize and is generally complicated to model analytically. In compact arrays the mutual interaction between elements can be significant, but this has proved difficult to include in an analytical calculation.

The author has previously demonstrated excellent agreement with experiment for predictions of the performance of a range of free flooding ring transducers, both singly and in coaxial line arrays [1][2][3]. Such coaxial line arrays have been shown to provide a high power low frequency source which is omnidirectional in the plane perpendicular to the axis of the array. For a *directional* low frequency active sonar array to provide useful directivity, such an array would be required to achieve a front-to-back ratio of at least 10dB.

DRA has previously demonstrated a method of producing such a directional source using a volumetric array of flextensional transducers [4]. However, very little work has been published on how to achieve a compact directional array using free-flooding ring transducers. One difficulty is that ring transucers are not compact sources so it is often impossible to fabricate desirable array configurations using rings.

The author has studied a number of different configurations of volumetric ring transducer array. The example presented here, to demonstrate the technique, is a Diamond Array of 4 free flooding ring projectors. Projector sensitivities and horizontal and vertical beam patterns are predicted. The results exhibit a useful front-to-back ratio and good directivity patterns over a wide frequency band when the array is driven by a voltage input with phase differences of 90°.

2. MODELLING METHOD

The theoretical modelling described here is based on the PAFEC Finite Element code [5]. The finite element method is used to describe the dynamic behaviour of the actual ring structures and incorporates piezoelectric coupling [6]. The piezoelectric structure is excited by the application of a voltage with specified amplitude and phase.The surrounding acoustic fluid is described using the boundary element formulation via the Helmholtz Integral Equation (the simple Helmholtz model). Coupling between the fluid and the structure is enforced by invoking the correct continuity relations.

Owing to the relative thinness of the ring wall when compared to an acoustic wavelength, there is no likelihood of suffering uniqueness problems associated with the integral equation approach. There is no need to adopt the CHIEF or some related method [6].

3. THE RING TRANSDUCERS

The operational realization of a compact directional low frequency active free-flooding ring array might be expected to use large scale segmented rings. However, in this case a small scale conceptual study was conducted using DRA test rings made of solid PZT4 piezoelectric ceramic. The dimensions of the rings are as follows:-

Outer Radius	57.15	mm
Inner Radius	50.8	mm
Axial Height	28.0	mm

These rings are silvered on the inner and outer surfaces and poled in the radial direction. They are waterproofed using a layer of polybutadiene.

From a modelling point of view, the DRA small scale test rings have a distinct advantage, as they are radially poled. This allows for a perfectly axisymmetric structure. Thus, for a single ring, a simple axisymmetric structural model is sufficient, reducing computation time. When required to adopt a full 3D approach the mesh discretisation is purely governed by the expected variation in the surrounding acoustic field. For other ring designs, the mesh discretisation must accommodate any structural features present, as is the case for a segmented ring.

4. ARRAY CONFIGURATIONS

It is well known that two point sources separated by a quarter wavelength and driven with signals of 90° phase difference will produce a cardioid beam pattern. However, in this case, although a cardioid pattern is desirable in the horizontal plane, a narrow beam width is required in the vertical plane. This could be achieved by two coaxial line arrays spaced a quarter wavelength apart and driven with a 90° phase difference.

Helmer [7] describes two demonstrator arrays built for the German ATAS programme which follow this principle. These two arrays each consist of four transducers arranged in a rectangle with $\lambda/4$ horizontal and $\lambda/2$ vertical spacing. One of the arrays uses SPARTON ring shell (class V flextensional) projectors and the other uses British Aerospace class IV flextensional transducers. Helmer demonstrates that using these two arrays it is possible to obtain a front-to-back ratio of greater than 10dB over the whole frequency range of interest. DRA has also demonstrated a similar technique using a close packed volumetric array of class IV flextensional transducers [4].

Compact arrays are readily achievable with flextensional transducers [4][7] as they behave very much like ideal point sources. That is, they are very much smaller than a wavelength of the sound they transmit. In contrast, free flooding ring transducers are distributed sources. It is not possible to align two ring transducers $\lambda/4$ apart as the diameter of a free flooding ring is typically of the order of $\lambda/2$.

5. DIAMOND ARRAY.

As well as the rectangular array, mentioned above, which is not realizable using ring transducers, Helmer [7] mentions a possible alternative configuration that was considered for the ATAS array but not ultimately used. This alternative is not described in detail but it is understood that this was a diamond shaped array with both diagonals $\lambda/2$ in length (Figure 1).

This type of array may be realizable using some types of free flooding ring transducers. However, such an array may require to have a modified spacing as ring transducers typically have a diameter which is of the order of half wavelength of sound they produce

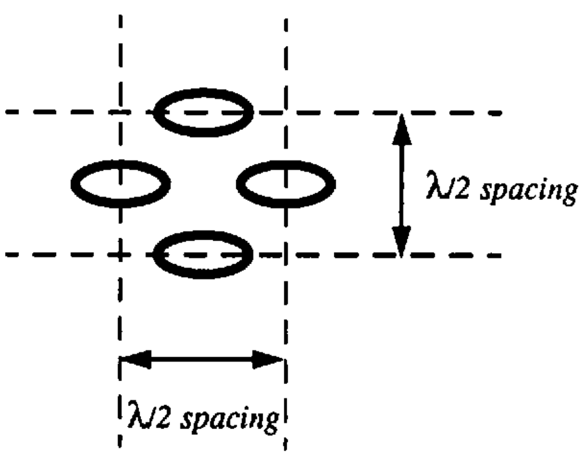


Figure 1 : Alternative Helmer Array

A diamond shaped array similar to that described by Helmer, but using four small DRA test rings, was modelled. The array described by Helmer had both "diagonals" (the horizontal and vertical separation) $\lambda/2$ in length. However, this was not possible using the small DRA test rings as the outer diameter of the rings is greater than $\lambda/2$ at their resonance. The version of the Helmer array studied here has the sides of the diamond $\lambda/2$ in length as shown in Figure 2. This gives a horizontal and vertical separation of greater than $\lambda/2$ at the resonance of the rings.

The array spacing should be optimized for either 7.5KHz (the resonance) or ideally 10KHz (the middle of the operating band). However, if the sides of the diamond are to be $\lambda/2$ in length, this can only be done for 7.5KHz. The spacing required for 10KHz cannot be achieved as two of the rings would overlap. Therefore, diamond shaped array with sides 10cm in length ($\lambda/2$ at 7.5KHz) was modelled.

PERFORMANCE PREDICTION OF A VOLUMETRIC ARRAY

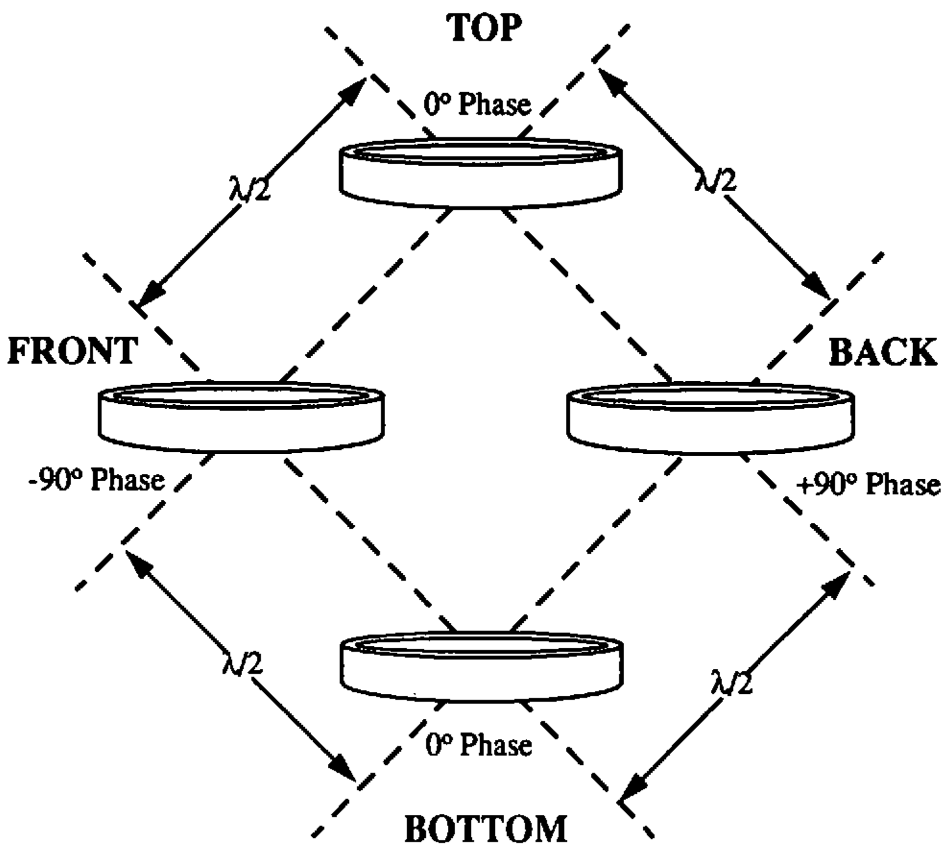


Figure 2 : Geometry and Orientation of the Diamond Array (not to scale)

6. DESIGN OF THE MESH

Exploiting the axisymmetry inherent in a single ring is impossible in this case and a full 3D approach is necessary. A three dimensional model of a 180° section of a small scale free flooding ring transducer was constructed from twenty noded piezoelectric brick elements [5]. As a one-to-one coupling is required between the acoustic boundary element patches and the wet surfaces of the structural elements, the density of the structural mesh is determined by the requirements of the acoustic mesh. The mesh should have as few degrees of freedom as possible to keep the run time to a minimum, while being sufficiently fine for an accurate representation of the surface acoustic pressure field up to the highest frequency of interest [6]. The largest dimension is in the circumferential direction which requires to be divided into 18 elements. As only frequencies up to 15KHz are to be considered the wall thickness and axial length of the ring are small relative to a wavelength, so one element is sufficient in each case. The mesh for this array is shown in Figure 3.

PERFORMANCE PREDICTION OF A VOLUMETRIC ARRAY

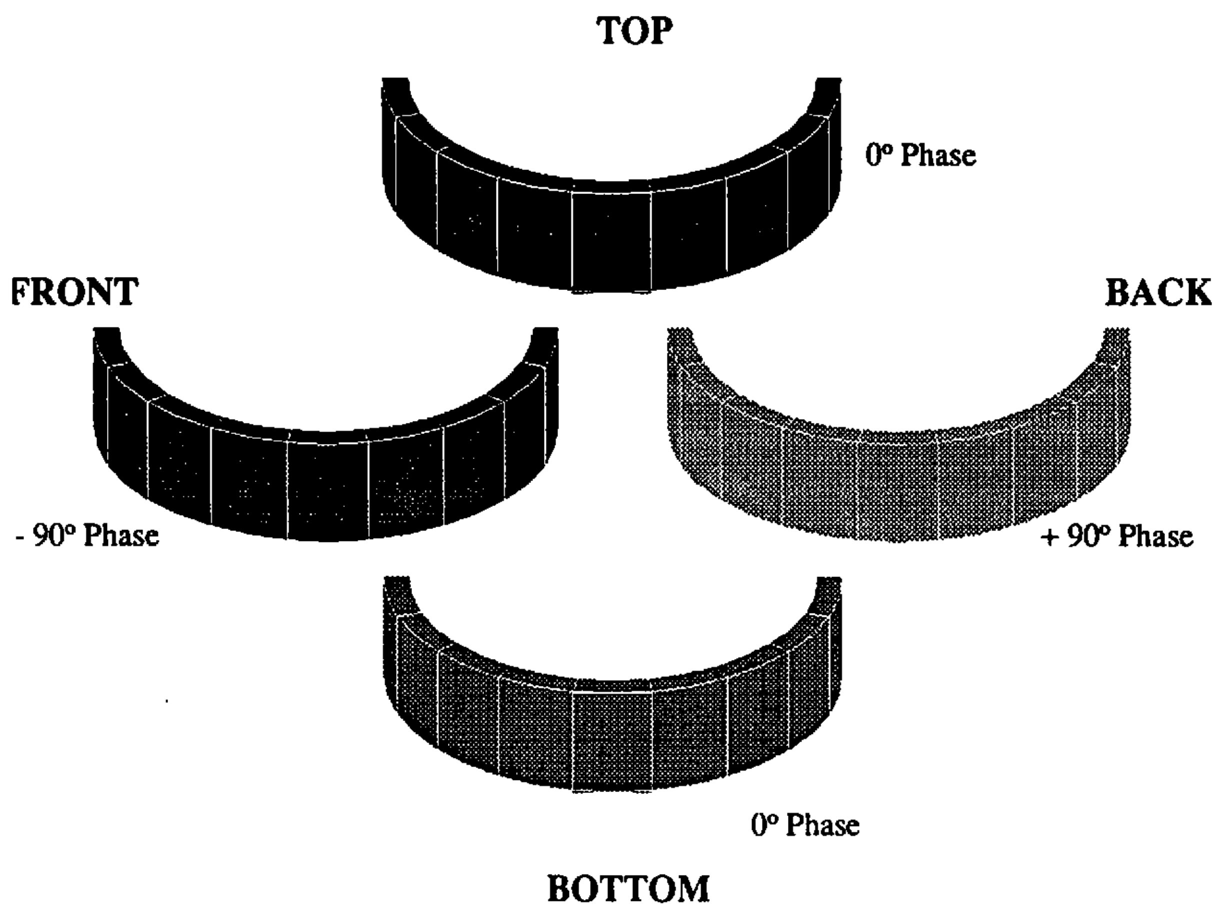


Figure 3 : Mesh of a Small Scale Four Ring Diamond Array Spaced λ/2 Along the Sides of the Diamond and Driven with 90° Phase Difference.

The basic model assumes that there are no structural losses in the device and the only damping is that due to the radiation damping effect of the fluid. However, the devices were waterproofed using a 5mm thick layer of Polybutadiene which adds significant damping to the structure. This structural damping is only significant around the resonance as the fluid damping dominates over the rest of the spectrum. When the effect of the waterproof coating is added to the model excellent agreement with experiment is obtained [1].

Although the damped models give results which compare more precisely with experiment, the undamped models are very meaningful and have therefore been included for clarity. Often the damping effect of the Polybutadiene coating can obscure some of the interesting features of the projector sensitivity and, in particular, it may mask the severe interaction effects which can occur when the array spacing is less than or of the order of half a wavelength.

PERFORMANCE PREDICTION OF A VOLUMETRIC ARRAY

If these small scale models are to be used to draw conclusions about the behaviour of a large scale array then the undamped results must be considered. Devices which have an oil filled rubber boot to provide their waterproofing, have significantly less damping than those which use a solid Polybutadiene coating.

7. DRIVE INPUT

To harmonically excite the fully coupled fluid-structure with piezoelectric coupling, a unit amplitude of 1 volt is applied to the outer electrode with the inner electrode earthed (grounded). (Note: our test scaled rings are radially poled). The phase difference was imposed by an appropriate real and imaginary voltage at one ring (or pair of rings) with reference to the other.

8. PROJECTOR SENSITIVITY

The projector sensitivity of an acoustic source defines the acoustic pressure at a specified point in the fluid when a unit alternating voltage is applied at its terminals. It is expressed in terms of dB re 1μPa and extrapolated back to unit distance. It is expressed as, 20 Log_{10} (acoustic output / electrical input).

The results presented here were calculated at specified points sufficiently far away from the Fresnel zone of the array and scaled by their distance, assuming spherical spreading. For this study four field points were chosen, all of them in the plane of the array, at 10m from the acoustic centre of the array. The directions of the field points from the array are referred to as FRONT, BACK, TOP and BOTTOM, as shown in Figure 3. The predicted Projector Sensitivities are shown in Figure 4.

Although there is a good front-to-back ratio over a reasonably large frequency band, this band does not coincide exactly with the operating band of the array. The best front-to-back ratios are, in fact, achieved at frequencies below the resonance of the rings and, therefore below the operating band. This is because the array spacing is actually optimized for about 5.3KHz (diagonals of the diamond = 14.14cm = $\lambda/2$ at 5.3KHz), which is below the resonance.

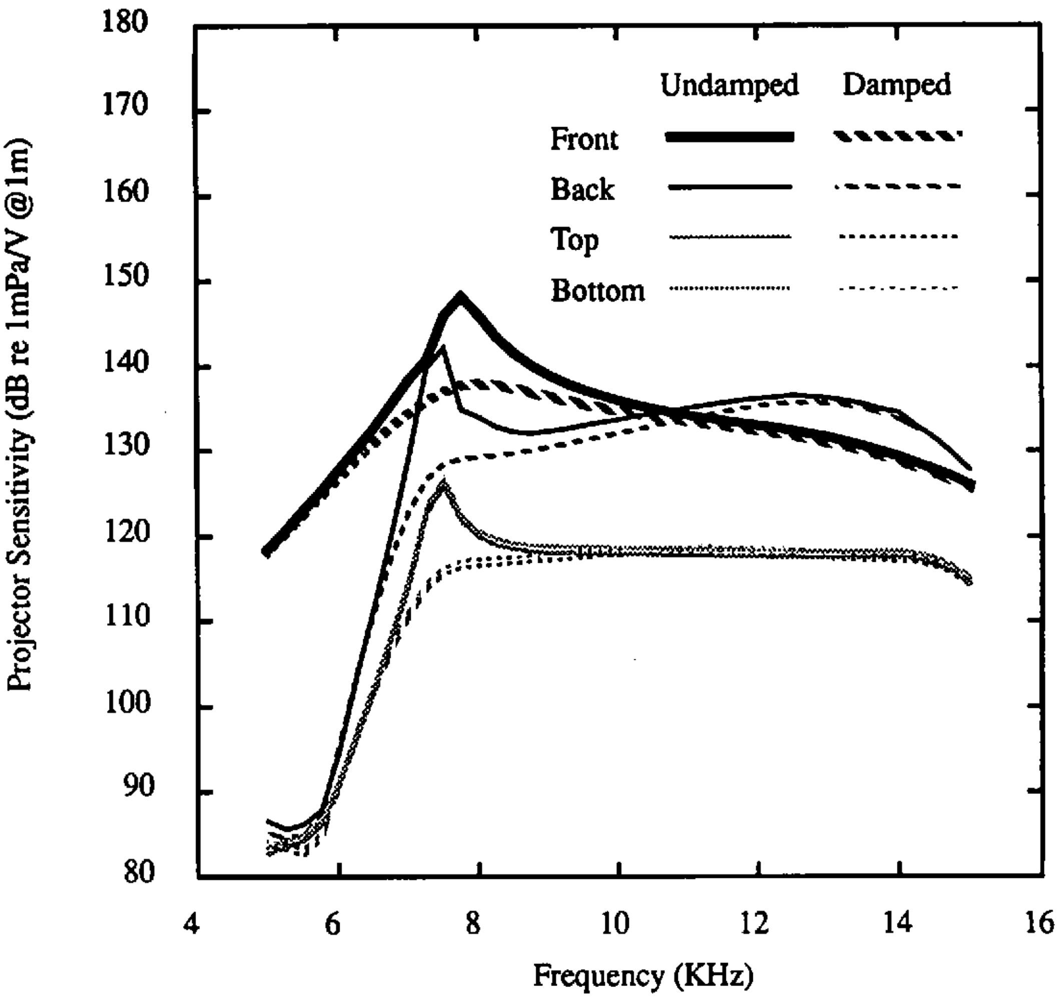


Figure 4 : Projector Sensitivities for a 4 Ring Diamond Array Driven with 90° Phase (sides of the diamond λ/2 at 7.5KHz)

9. BEAM PATTERNS

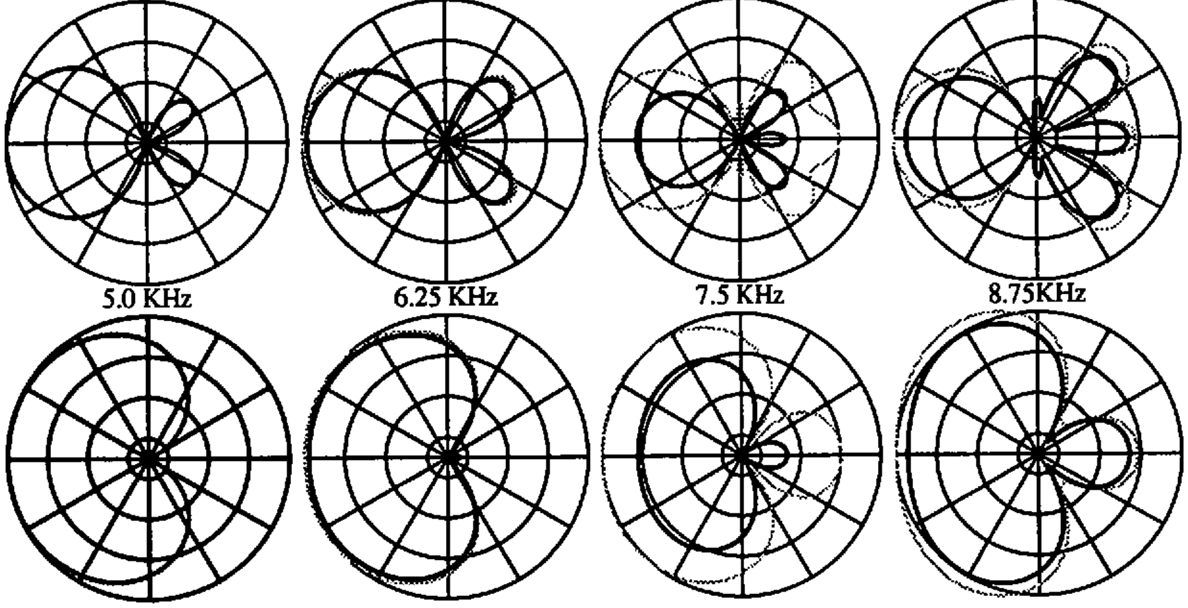
These are directivity polar plots with a range of 35 dB. The radial distance between concentric rings represents 10dB. The directivity as a function of angle is normalised to the radial direction for a conventional line array and to the forward direction (the FRONT as defined in above) for an interleaved array. Here we present two types of plot; a horizontal and a vertical. The vertical beam pattern is in the plane of the array, the horizontal plane is normal to it. The orientation of the beam patterns in the vertical plan is exactly that for the arrays as illustrated in Figures 2 and 3.

The beampatterns are shown in Figure 5. It is clear that the damping has little or no effect on the beam patterns except around the resonance of the rings (7.5kHz). However, at the resonance the effect of the damping much less dramatic for the Diamond Array than for other array configurations previously studied by the author. This may be advantageous in an array of devices which have significantly less damping than those considered here.

The vertical beam patterns exhibit a strong forward beam and there are three distinct rear radiating lobes which increase in magnitude with increasing frequency. At the highest frequencies these lobes can exceed the main beam in magnitude.

As mentioned above, the array spacing is optimized for 5.3KHz so it is not surprising that the idealized cardioid beam pattern in the horizontal plane is seen in the 5KHz plot. This optimum pattern deteriorates with increasing frequency. In addition, at higher frequencies (above about 8KHz) main horizontal beam develops major side lobes which appear at about 60° to the forward direction. These must be controlled if this array configuration is to prove of value.

Vertical



Horizontal

*Figure 5 : Comparison of **Damped** and Undamped Directivity Beam Patterns.*

10. COMPACT ARRAY

In an attempt to move the optimum cardioid beam pattern more into the operating band, a close packed array was devised in which the middle rings were almost touching. This had the diagonals of the diamond 11.6cm in length ($\lambda/2$ at 6.5kHz). This is still below the resonance of the rings but closer to the operating band.

Of the two configurations the compact array is the more attractive as it produces the required front to back ratio over a larger frequency band, while also achieving good directivity polar plots. In particular there is no significant broadening of the main horizontal beam into major side lobes which was seen with the original array.

11. DISCUSSION

It is useful to compare the Diamond Array with a four ring line array. The FRONT and BACK directions of the Diamond Array can be directly compared with the RADIAL direction of the line array. However, the projector sensitivities in the forward direction are about 5dB less than for the line array over most of the operating band. This is not the case for other directional volumetric arrays previously studied by the author. This difference is particularly evident when comparing the damped results. The TOP and BOTTOM directions of the staggered array can be directly compared with the AXIAL direction of the line array. The level of sound being directed towards the sea surface and bottom would be slightly greater with the Diamond Array than the line array.

It may be possible to optimize the horizontal cardioid beam pattern produced by the Diamond array by varying the amplitude of the drive on the four rings. For a pure cardioid directivity pattern, derived from an effective dipole (in this case the two middle rings) and an effective monopole (here the top and bottom rings), it is necessary to impose correct amplitude shading [8]. To maintain this ideal directivity the shading must be frequency dependent which may result in a less than maximum projector sensitivity.

12. CONCLUSIONS

This study was intended to demonstrate how the performance of close packed volumetric array of free flooding ring transducers could be predicted using the PAFEC FE/BE code. The Diamond configuration chosen was intended as a *directional* low frequency active array for various applications which require a front-to-back ratio of at least 10dB.

It was shown that this array offers a front to back ratio in excess of 10dB over an octave in both configurations when driven with 90^0 phase differences between projectors. However, this octave cannot be made to coincide precisely with the operating band of the rings, even using the close packed configuration (optimized for 6.5KHz). The optimum spacings (optimized for 7.5 or 10KHz) are not achievable with these rings as they are distributed sources. Over the optimal frequency band this array exhibits attractive beam patterns, with few side lobes.

13. REFERENCES

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