PERFORMANCE PREDICTION OF AN ARRAY OF FREE FLOODING RING TRANSDUCERS

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1. INTRODUCTION

There is a growing interest in compact, low frequency, active acoustic sources for a wide variety of underwater research and for possible sea bottom survey applications. Line arrays of free flooding ring transducers are currently being considered for this purpose. The performance of arrays of rings is difficult to predict as the behaviour of the individual projectors is not well understood 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 ultimate purpose of this work was to predict the performance of a co-axial line array of four large segmented free-flooding ring transducers manufactured by Sparton of Canada. Before undertaking this task, it was decided to make a preliminary study of small ceramic rings which would be more simple and quick to model than the large Sparton rings and which could be easy and cheap to study experimentally. Small solid ceramic rings made of PZT4 were chosen. The dimensions of the rings were as follows:-

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

These rings were silvered on the inner and outer surfaces and poled in the radial direction. They were waterproofed using a layer of polybutadine. These devices had three major advantages over the Sparton rings as suitable devices for perfecting the new modelling techniques :-

1. Being small and operating at a relatively high frequency, the acoustic characteristics of these devices could easily be measured in the small tank in the DRA Transducer Technology Section.

2. This type of ring is easy and cheap to buy as it is a standard size routinely manufactured by all the major ceramic firms.

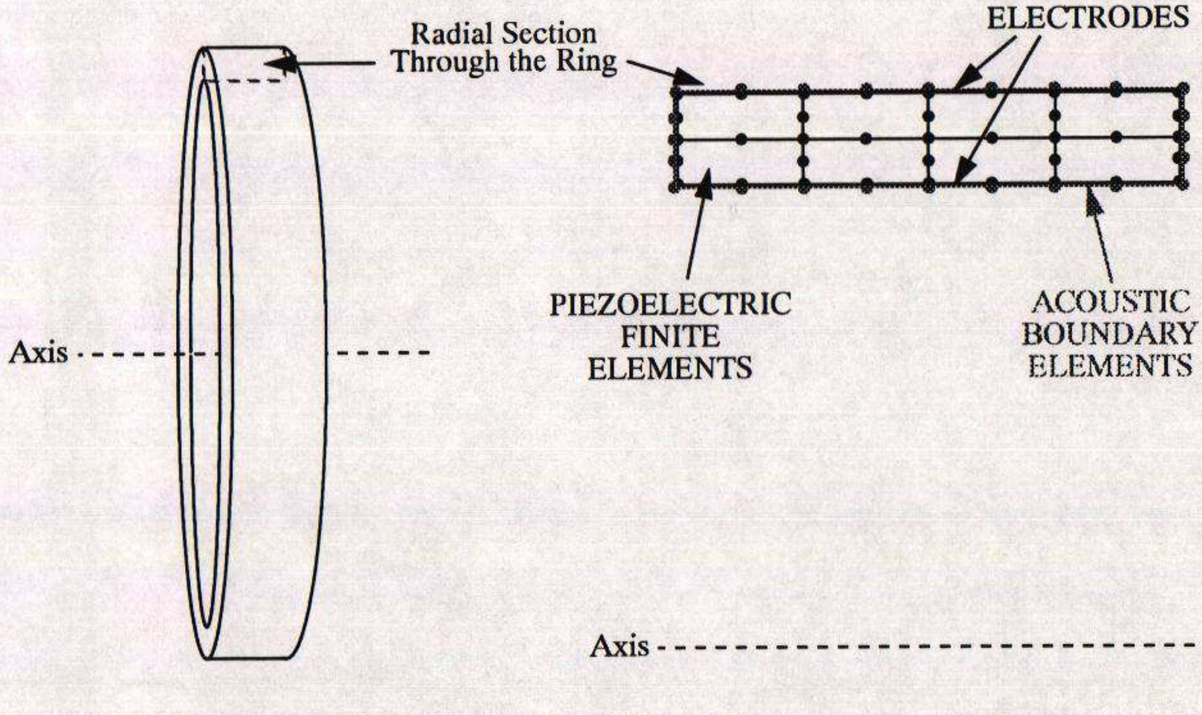
3. As these rings are truly axisymmetric in geometry all that is required is a simple 2-dimensional model, which is simple to design and quick to run even on the limited hardware available at the time.

Here projector sensitivities, far field directivities and admittance loops of the devices, singly and in arrays, are calculated using a hybrid Finite Element/Boundary Element form of the

Helmholtz Equation. Various models based on the PAFEC Finite Element Code (Level 7.4)[1] are considered. Mutual interaction between projectors is implicit in the method. The F.E./ B.E.results are compared with measurement and with a simple analytical model.

2. SINGLE RING MODEL

As these simple ceramic rings are truly axisymmetric in geometry, the structure was represented by a 2-dimensional generator and the structure is assumed to be a solid of revolution of this generator about the horizontal axis (x-axis). The generator simply consists of a rectangle (i.e. a radial section through the ring) as shown in Figure 1. This model fully exploits the symmetry of the device.



(a) Ceramic Ring TransducerShowing the Generator (Radial Section Through the Ring) which defines the mesh.

(b) Axisymmetric Mesh

Figure 1 - Axisymmetric Model of a Simple Ring Transducer

An axisymmetric Fourier analysis was performed in which only modes of circumferential harmonic number N=0 were considered [1]. The characteristics of a ring were found using the PAFEC code and then presented in forms more familiar to transducer designers.

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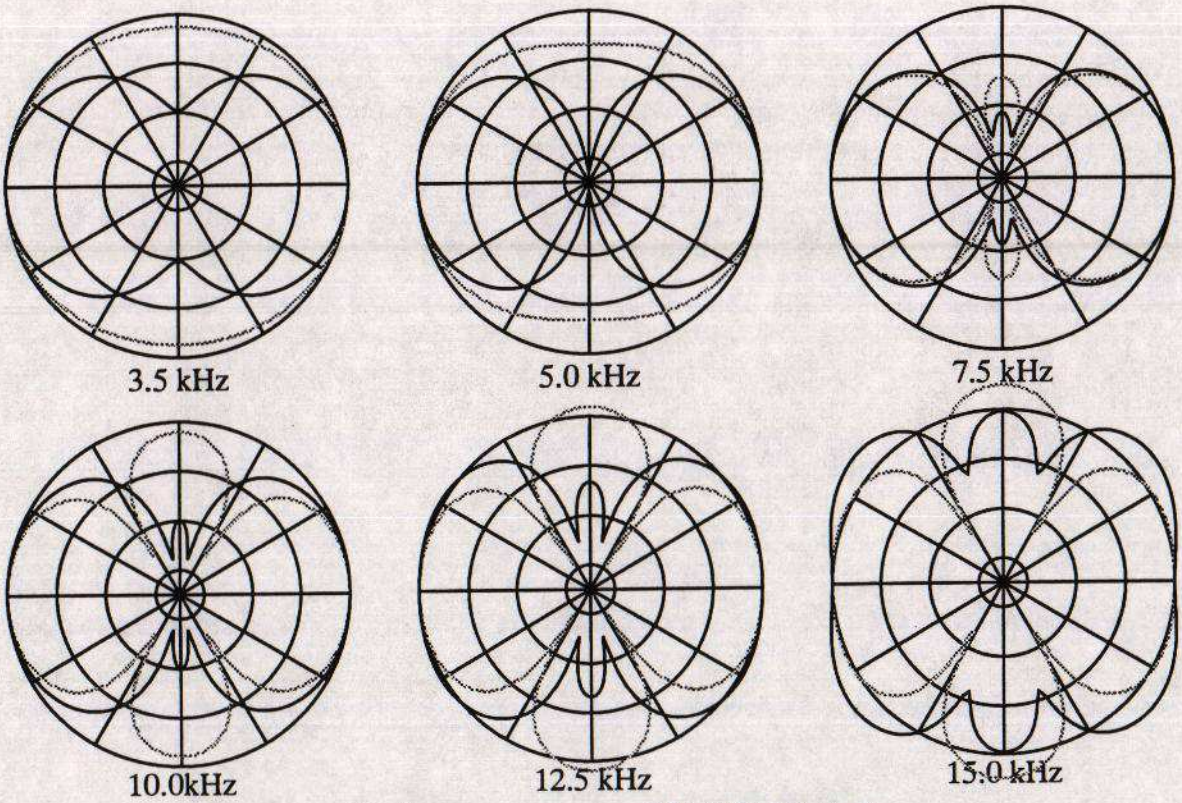
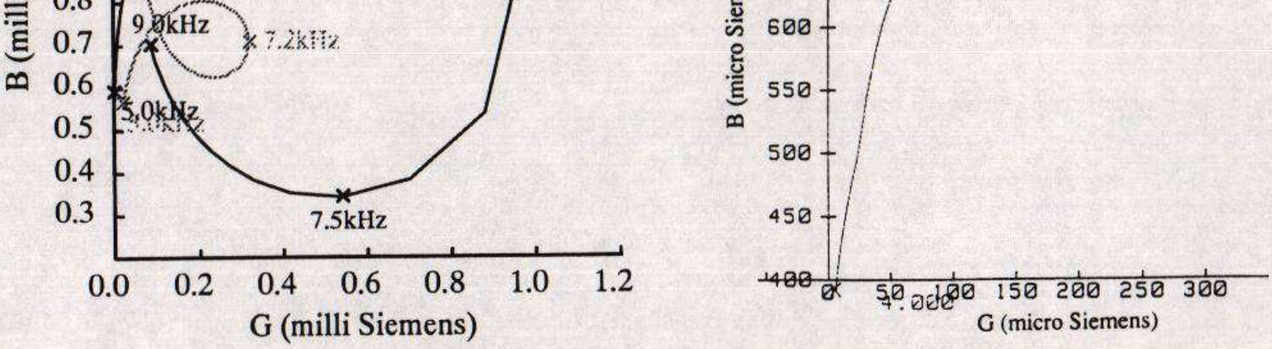


Sherman and Park ——— F.E./B.E. Method ———

Figure 3 .- Directivity in terms of Normalized Projector Sensitivity (dB)



Calculated Loop (With Damping) Measured Loop

Figure 4 - Admittance Loops for a Single Ring in Water

The boundary element formulation of the Helmholtz solution method [2] was used to obtain the far field pressures due to radiation from the ring. The performance of the rings was well described over the frequency range of interest. However, at resonance the calculated projector sensitivity shows a pronounced peak which is not found experimentally (Figure 2) [3]. It is later demonstrated that this discrepancy is due to the damping effect of the polybutadiene coating used in the experiment to waterproof the ring.

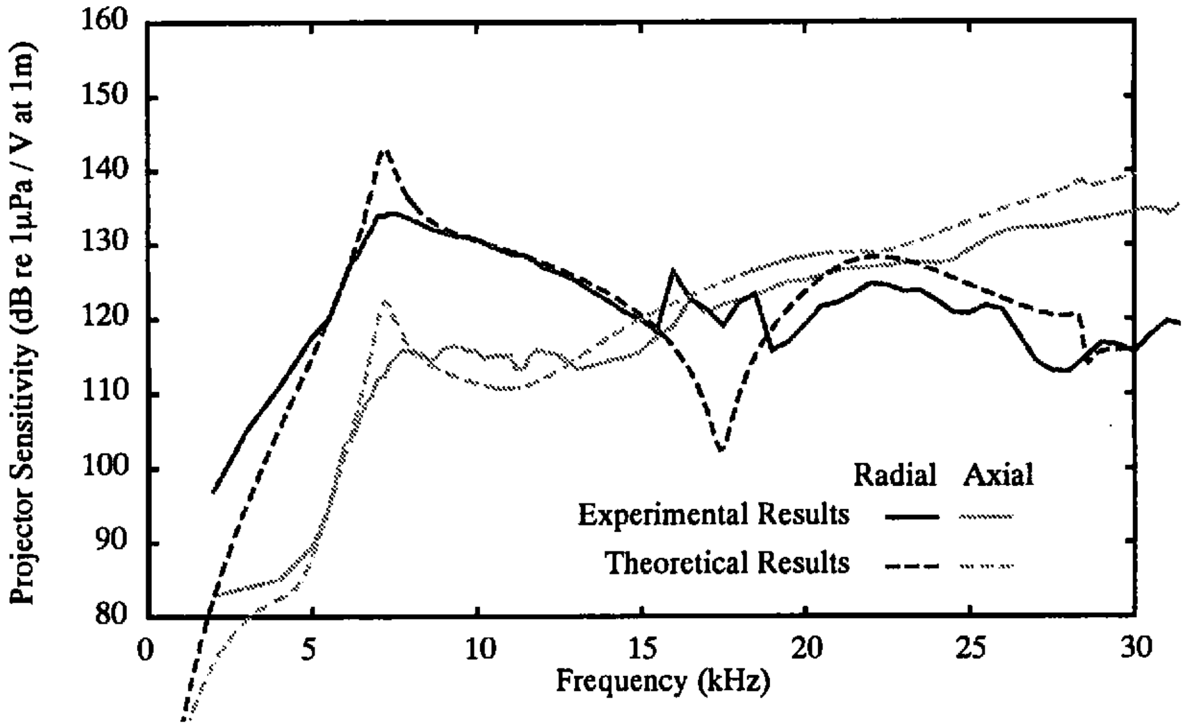


Figure 2 - Projector Sensitivity of a Single Ring

The normalized asymptotic far field pressure radiated by a single ring was calculated in 2 degree steps around the device. The beampatterns calculated in this way were compared with the Sherman and Parke, toroidal approximation (Figure 3)[4]. The directivities predicted by these two methods are significantly different but broadly agree at the radial resonance of the ring, around 7.5kHz. Unfortunately no accurate experimental results are available for comparison.

It is possible [2] to use the new PAFEC Acoustics package to calculate the admittance loop of a free-flooded piezoelectric ring transducer in water (Figure 4). Using a simple model which includes radiation damping but no structural damping the frequencies at which the loop occurs are quite well predicted by the PAFEC model, but its magnitude is not. By simply including the structural damping due to the polybutadiene coating better agreement with experiment is obtained [3].

Hardie [2] has shown that for longer cylinders (tubes rather than rings), which have significant cavity resonances, a mesh with explicit interior fluid finite elements will more accurately model the cavity resonance. To do this a hybrid boundary element/finite element representation of the fluid was used. The structure was enclosed in a 'fluid bag' of axisymmetric fluid finite elements, which was surrounded by the fluid boundary element (Figure 5).

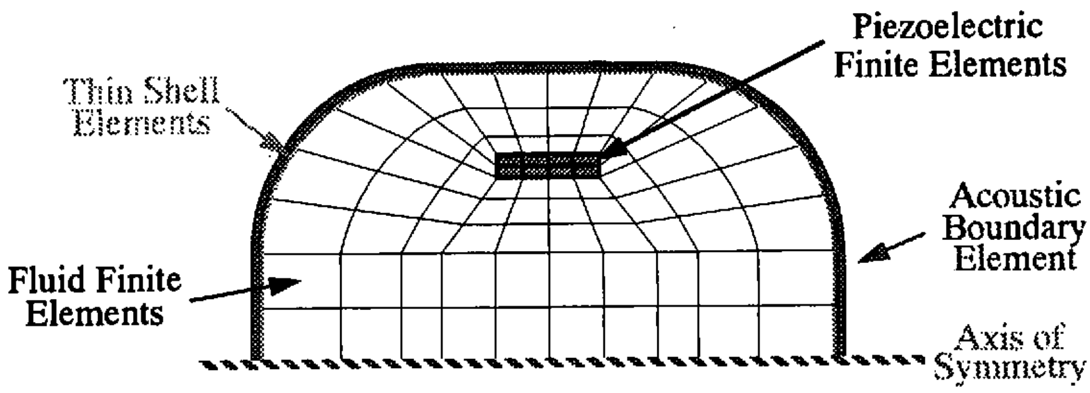


Figure 5 - Hybrid "Fluid Bag" Model

Ambiguities in the surface normal can arise when considering a discontinuous boundary element surface with, for example, corners or edges. For the solution of the far field these ambiguities are somewhat reduced by the integration procedure. However, the boundary element surface was chosen to be a smooth curve, following the recommendations. Unfortunately acoustic boundary elements cannot be coupled directly to pressure-based finite elements. However a method has been devised [2] whereby the exterior boundary elements are coupled to the interior fluid finite elements via axisymmetric shell elements. A suitable choice of material properties and restraints produces an almost transparent coupling. All displacement degrees of freedom on the shell elements are restrained except those in the normal direction.

The Projector Sensitivity results from this fluid bag model were compared with the results from the direct Helmholtz model showing that the difference between the two sets of results was negligible so either method may be used. In this particular case, of a single ring, the direct method is easier and quicker. However, in the case of an array of elements a fluid bag may be used to simplify and reduce the length of the acoustic boundary, thereby reducing the run time. Hardie [5] demonstrates that, using a fluid bag and an approximate formulation for the acoustic boundary element even, faster predictions may be obtained.

Useful near field pressure contour plots can be obtained directly from the "fluid bag" model or, with significantly less computational effort, by including display elements in a direct boundary element model [6].

3. ARRAY MODELS

Of particular interest, in respect of the ultimate task of modelling the large segmented Sparton rings, is the case of a four element co-axial line array. It was anticipated that the scale of final problem would be beyond the scope of the limited computing power at our disposal unless an idealized array, in which all elements were driven identically, was assumed and all possible symmetries were fully exploited.

As array interaction had never before been studied using the PAFEC Acoustic code, the preliminary study of the small axisymmetric rings was intended to perfect the method for such an analysis. It was also required to show that it was feasible to make full use of any symmetry. The main difficulty that could be foreseen was that so far PAFEC had only been used to model systems in which there was a single closed acoustic surface. It remained to be demonstrated that PAFEC could handle the topological anomalies inherent in a system with more than one closed acoustic surface.To this end it was decided to progress towards the ultimate goal of a four ring array in simple stages. Having satisfactorily demonstrated the use of the PAFEC Finite Element Code, and in particular the Acoustics Package, for modelling one simple free-flooded piezoelectric ceramic ring [6], the same methods were first applied to two and then four rings [7].

4. TWO RING ARRAY MODEL

As a first step an acoustic plane of symmetry [7] was added to the single ring model, perpendicular to its axis, to create the effect of the presence of a second ring. The results from this model were then compared with those from an explicit two ring array model, in which the two dimensional generator for the second ring was defined in the same way as the first. In both models the two rings were assumed to be identical, connected in parallel, and driven in phase by the same sinusoidally varying voltage. Only this idealized case can be modelled using the plane of symmetry but the explicit two ring model would allow variations in the two devices and differences in the amplitude and phase between the driving voltages.

The projector sensitivity and directivity results from the two models, calculated by the direct Helmholtz method, were found to be identical and consistent with what might be expected from a two ring array. Unfortunately, at this stage in the analysis, no comparison was made with experiment as the results were not available.

5. A FOUR RING ARRAY MODEL

An acoustic plane of symmetry was added to the explicit two ring array model described above, to create the effect of a four ring array. The projector sensitivity and directivity results from the two models, calculated by the direct Helmholtz method, were again compared with similar results obtained from an explicit model. Again the results were found to be identical.

A further comparison was made between the results from these two models and those from a hybrid fluid bag model [7]. As predicted by Hardie [2], it was found that for rings such as these, with a short axial length, there was little to be gained from using this method. However, the fluid finite elements which formed the enveloping bag proved very useful for displaying the near field (discussed later). This could, of course, have been done using the display elements [7] at a lower cost in terms of C.P.U. time. The fluid bag has the advantage of providing a single closed acoustic boundary element surface, thereby removing the topological anomaly which arises from a number of connected closed surfaces.

As with the single ring the projector sensitivity of the array was well described over the frequency range of interest, except at the resonance. At resonance the calculated results showed a pronounced peak which was not found experimentally [2]. Although these first four ring array models were very simple and did not include any damping effect due to the coating it quickly became apparent that this must be included to obtain good agreement with experiment at resonance.

The normalized asymptotic far field pressure was calculated in 2 degree steps round the array. The beampatterns calculated in this way were compared with the Sherman and Parke, toroidal approximation [4]. The directivities predicted by these two methods were significantly different. The results of the simple undamped PAFEC model and the Sherman and Parke approximation differed most markedly at array spacings of less than $\lambda/2$. The Sherman and Parke model does not include any interaction effects [4]. However, rather surprisingly, in this particular case the Sherman and Parke results showed better accord with measurement (discussed further in the next section).

6. THE WATERPROOF COATING

As mentioned in Section 1, the rings were waterproofed using a 5mm thick layer of polybutadine. This coating material was chosen because it has very similar acoustic properties to water. It was, therefore, not thought necessary to include it in any of the simple models used so far. However, the major difference is that, unlike water, this viscoelastic material can support shear waves. It is, therefore, possible that the coating may add significant damping to the structure. Measurements made on similar, but uncoated, rings suspended in oil, gave projector sensitivity results which, look more like those obtained from PAFEC. This would suggest that the polybutadiene coating may indeed contribute some damping.

Although the PAFEC code has facilities for including material damping, a full viscoelastic material model is not, at present, implemented. It would have been possible to add the 5mm thick coating to the existing mesh explicitly, using the PAFEC 8-noded isoparametric element for axisymmetric fourier applications. However, it was felt that this would give a very poor representation of the behaviour of the coating.

If we assume the coating is acoustically like water and its only effect is to add damping then it might be reasonable to consider the original mesh of the ring without the polybutadiene coating and with the damping due to the ring applied directly to the piezoelectric ceramic.

One possible method of applying the damping due to the polybutadiene is using the PROPORTIONAL.DAMPING module [1]. In this module viscous damping is modelled by a damping matrix. The material has a complex Young's Modulus and the imaginary part ($\tan\delta$) modifies the stiffness matrix. Assuming equipartition of energy, the effective damping factor can be estimated by scaling the value for the polybutadiene coating by the relative volumes, giving an effective damping factor, $\tan\delta = 0.13$.

The projector sensitivity results from this damped model are shown in Figure 6 along with the results from the simple undamped, uncoated model and the experimental results for comparison. It can be seen that the new model gives excellent agreement at resonance. As expected, the structural damping is only significant around the resonance as the fluid damping dominates over the rest of the spectrum.

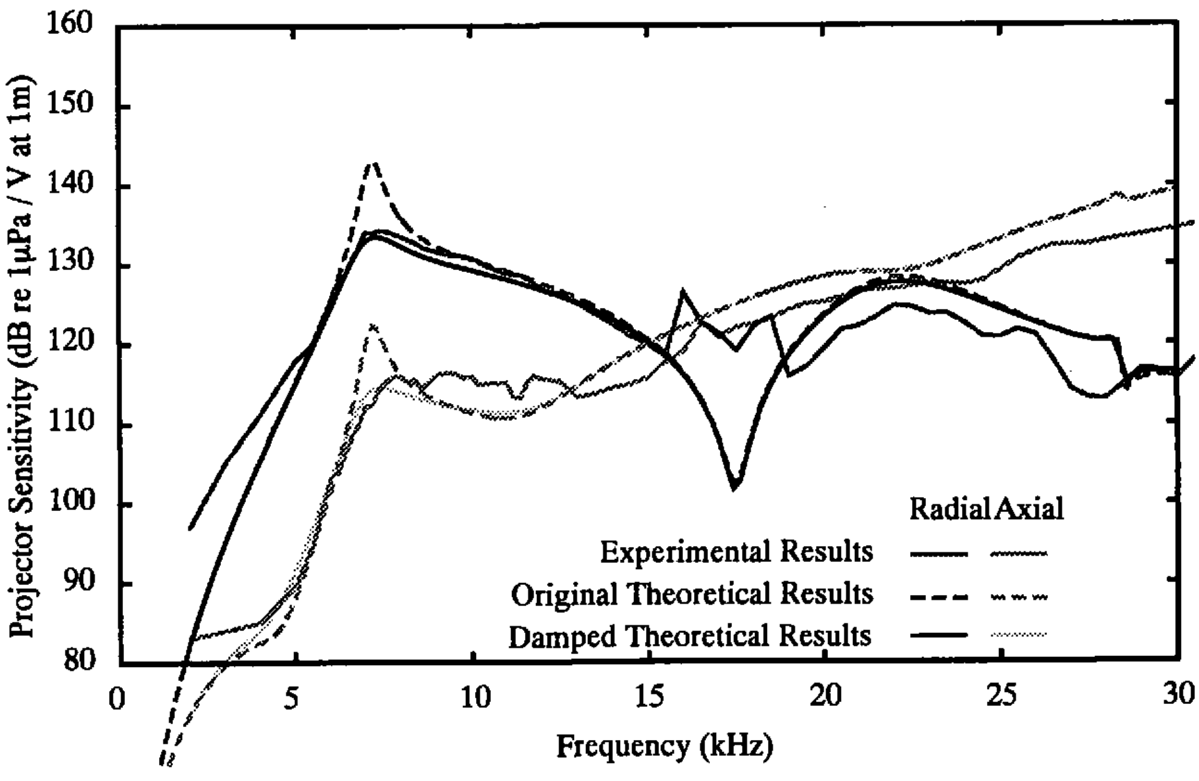


Figure 6 - Projector Sensitivity of a Single Ring

In general when an array's spacing is less than $\lambda/2$ significant interaction occurs between the elements and the directivity is not simply the sum of the directivities of the individual elements. However, in the particular case of the free flooded rings coated with polybutadiene, the directivity is significantly affected by the coating. The damping due to the polybutadiene acts to mask the elements from the influence of the others, giving beam patterns which exhibit little interaction. This was clearly seen by comparing the undamped results (no coating) with the damped results (with coating) [7]. The Sherman and Parke, toroidal approximation neglects interaction completely [14] and fortuitously shows some agreement with experiment. However, the damped PAFEC model with its correct implicit inclusion of interaction exhibits much better agreement with experiment than Sherman and Parke, as it should.

It was this discovery of the significance of the damping effect of the waterproof coating that triggered a deeper study of coated rings. Macey [8] considers the coating material explicitly in the finite element description of the structure.

7. CONSIDERATION OF A SPARTON SEGMENTED RING

It was hoped that the lessons learned and the methods established in this preliminary study could be used with similar success for the large Sparton segmented rings. The most significant differences between the Sparton rings and the simple rings considered so far are :-

1. The Sparton rings are not strictly axisymmetric.

2. The method of waterproofing used on the Sparton rings is completely different from the polybutadiene coating used on the simple rings. Each Sparton ring is enveloped in an oil filled rubber boot. This was designed to be less lossy than the polybutadiene.

3. Unlike the one piece rings studied previously, the components in the Sparton rings are assembled with resin bonds. These resin joints, although very thin, are known to be very compliant and can contribute significantly to the properties of the finished structure.

Given the limited computing power available and the success of the axisymmetric models used in the preliminary study there was a strong case for considering the possibility of an axisymmetric model of the segmented Sparton rings. Each device is not strictly axisymmetric, being composed of forty groups of ceramic plates and metal wedges round the circumference. The direction of polarization is tangential. It was, however, hoped that suitable composite material properties could be derived to represent the structure by a two dimensional model. Such an equivalent composite would be piezoelectric and would combine the properties of the ceramic plates and the metal wedges.

As the PAFEC axisymmetric piezoelectric elements do not permit tangential polarization [1], it was quickly concluded that, if accurate results were to be achieved, a three dimensional model would be required. A mesh of a 9 degree wedge section of the device was constructed from three dimensional 20-noded elastic brick elements and incorporating acoustic boundary elements [9]. Bonin et al. [10] compare the results from this model with those from an axisymmetric model of the same device, based exclusively on the finite element method using the Canadian MAVART code.

8. CONCLUSION

The PAFEC Finite Element code with the Acoustic Boundary Element enhancement has been shown to produce projector sensitivities, admittance loops, directivities and pressure contour plots which, where results are available, compare very well with experiment for single elements and arrays. The usefulness of the code as a tool for transducer and array designers is evident.

Following this initial study of ring arrays, further work has been conducted on a variety of aspects. The computational task involved in deriving performance prediction is considerable and work progresses in reducing this effort. Hardie's idea [5] shows promise, with the possibility of extending these methods to cope with large arrays with additional structures. The importance of correctly incorporating damping losses is manifest for accurate array performance predictions. The investigations of Macey [8] attempt to address these issues in a more rigorous manner than discussed here. Other computational methods exist for ring modelling. The paper by Bonin et al. [10] compares the author's three dimensional hybrid F.E./ B.E. model of a Sparton ring with an axisymmetric model based exclusively on the finite element method.

9. REFERENCES

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