FE/BE MODELLING OF TRANSDUCER INTERACTION

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1. INTRODUCTION

Interaction between transducers is an important consideration in the design of high power active sonar arrays. Modelling predictions of array performance are of benefit to sonar array designers, reducing the requirement for costly prototype designs. To date modelling of array interaction has been broadly limited to analytical methods [1], but these are confined to particular types of transducer, usually piston stacks in an infinite baffle. The development of finite element and boundary element (FE and BE) techniques, coupled with the expansion in computing power allows the interaction problem to be studied using numerical techniques. These methods are applicable to a range of transducer types in any array configuration.

FE/BE modelling can be used to predict the change in performance of the individual transducers within an array, compared to that of a single transducer in free-field conditions, as well as that of the whole array. In this way, it is possible to determine whether an intended configuration can be driven at high levels with satisfactory results or whether there are likely to be regimes of, for instance, negative conductance which could damage both the transducer and its electrical drive chain. This avoids the problem of building a prototype array where transducers or amplifiers consistently fail. Previous work [2] has demonstrated the application of FE and BE methods to calculate the mutual impedance matrix for the transducers in an array. This paper examines, in particular, the electrical response of the transducers within an array, as variation of these can be critical to amplifier stability.

A vertical line array of free-flooding rings (FFRs) is considered, with varying spacings between the transducers. FFR projectors have been modelled extensively and the models of a single FFR transducer are extremely well validated [3]. The technique can be applied to any type of projector which can be modelled by FE/BE methods. An inter-element spacing of $\lambda/3$ has been used as standard. This figure is not regularly encountered in array analysis, however, it is typical of the minimum spacing physically possible with FFRs. The array layout for a five ring array is shown in Figure 1. The analysis details are provided in Section 3 of this paper.

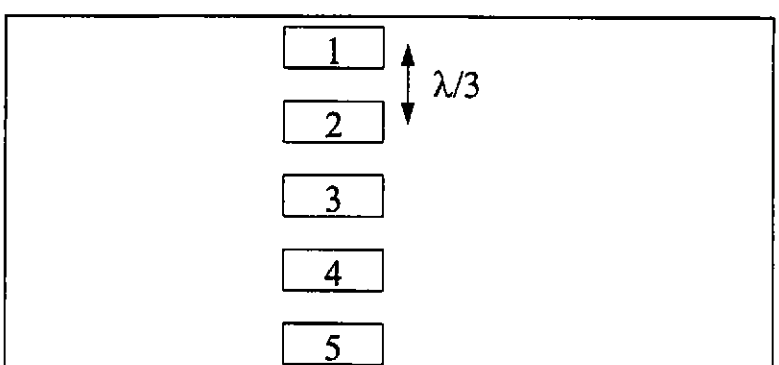

Figure 1; Alignment and spacing of elements in a five ring array

The conductance, G, of each element within the various array configurations has been calculated over a frequency range of 5-10kHz (resonance occurs at approximately 7.5kHz). Conductance is likely to be the most critical parameter to the designer of the power train, although phase angle may also be very important. As a consequence, this paper discusses the magnitude of conductance only.

2. MODELLING

The modelling has been carried out using Level 8.5 of the PAFEC FE and BE code [4]. The FE method is used to describe the structure and incorporates piezoelectric coupling. The surrounding acoustic fluid is described using BEs. Coupling between the fluid and the structure is enforced by applying the correct continuity relations. The Helmholtz Integral Equation is solved for a hybrid FE/BE model.

The FFR used for this study is the DERA Test Ring. This is constructed from a solid piece of radially poled PZT4 piezoceramic, which is silvered on the inner and outer surfaces to create the electrodes. An axisymmetric model is adopted for each FFR in the axial line array following [3].

Each projector was modelled explicitly, so that the effects of, for example, one FFR failing (thereby removing the symmetry of the problem) could be investigated. The damping due to the polybutadiene waterproof coating has been included in the representation. This is expected to reduce the interaction by shielding each projector from the effects of the others.

The electrical response of each transducer is calculated by applying a unit voltage across the terminals of the device and measuring the resulting current components. The PAFEC code has features which allow the admittance data to be easily extracted. There is also a facility in PAFEC which enables the mutual impedance matrix of an array to be calculated. This is discussed in an earlier paper [2]. The mutual impedance is defined by:

$$I_{i,j} = \frac{F_{i,j}}{V_i}$$

where $F_{i,j}$, is the total force on transducer$_j$ when transducer$_i$ is driven and V_i is a representative measure of the velocity on the surface of transducer$_i$. There are difficulties with the above definition of impedance when applied to FFRs, since these devices are not of simple topological form with inner and outer surfaces generally in anti-phase.

$F_{i,j}$ can be defined by:

$$F_{i,j} = \int_{transducer\ j} p_i \, dA$$

where p_i is the pressure on transducer i and A is the area of its radiating face.

V_i can be defined by

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$$V_i = \sqrt{\frac{\int_{\text{transducer}\,i} |V|^2 \, dA}{A}}$$

These definitions are to some extent arbitrary and are problem dependent. Other choices can be made and further investigation is necessary to establish the best practical set of definitions.

Two techniques can be applied to calculate the impedance matrix. In the first method, an uncoupled acoustic calculation is carried out, taking the surface velocities from a previous fully coupled analysis. The second method performs an equivalent calculation but with many right hand sides in a fully coupled vibro-acoustic analysis. This formulation is closer to some experimental methods for estimating mutual impedance in arrays and is therefore more amenable to direct experimental verification.

In both methods, a table representing the mutual radiation impedance matrix is calculated. Examining each term in the matrix gives a quantitative measure of the influence of one transducer on another.

3. ANALYSIS DETAILS

The conductance of a single FFR under free-field conditions was calculated. A second element was then added, with an inter-element spacing of 8λ/3. This spacing was successively halved to 4λ/3, 2λ/3 then λ/3 for the two ring array.

Conductance was also calculated for three ring, four ring and five ring arrays at the standard λ/3 spacing. For brevity only the five ring array is considered in detail here. Because of the symmetry inherent within the arrays, it was not necessary to calculate conductance for every projector, e.g. in the five ring array, Ring 1 is equivalent to Ring 5 (both outer rings), Ring 2 is equivalent to Ring 4 (both inner rings) and Ring 3 is the central ring (see Figure 1).

To demonstrate what happens when a projector fails, various rings within the five element array were set to open circuit. The conductance characteristics were calculated for the remaining four elements when firstly, the central element (Ring 3) and secondly an inner element (Ring 2 or 4) fails. Human error can also play a part. The conductance curves for the four remaining elements were also calculated when the centre element (Ring 3 in a five ring array) is connected in reverse phase. Within the FE/BE technique it would also be possible to show the transmit voltage response (TVR) and beampatterns and the perturbations to them when elements fail. However, this has not been covered in this paper.

The various analysis cases are summarised below:
- Single element;
- Two elements, spacing= 8λ/3, 4λ/3, 2λ/3, λ/3;
- Five elements spacing = λ/3;
- Perturbation 1: Five elements, spacing = λ/3, central element (Ring 3) open circuit;
- Perturbation 2: Five elements, spacing = λ/3, inner element (Ring 4) open circuit;
- Perturbation 3: Five elements, spacing = λ/3, phase of central element (Ring 3) reversed.

4. RESULTS

The interaction effects between transducers are illustrated by Figures 2 and 3. Figure 2 shows the conductance of a single transducer, while Figure 3 shows the conductance of one of a pair of transducers as the inter-element spacing is reduced. Effects are seen to be small when spacing is greater than a wavelength but some reduction in conductance is observed at $2\lambda/3$ and a significant drop to about 0.75 the conductance of a single element is seen as the spacing is reduced to $\lambda/3$. There is also a distinct drop in resonant frequency, as if the mutual interaction has both real and imaginary components (radiation reduction and mass loading).

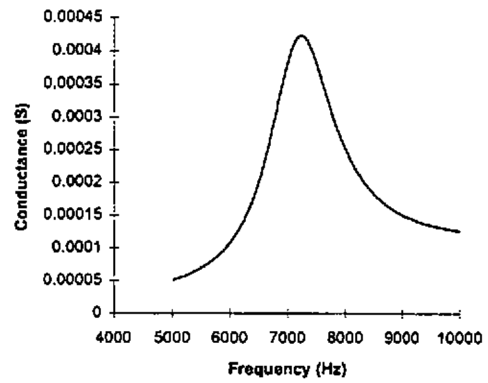

Figure 2; Conductance of a single ring in free-field conditions

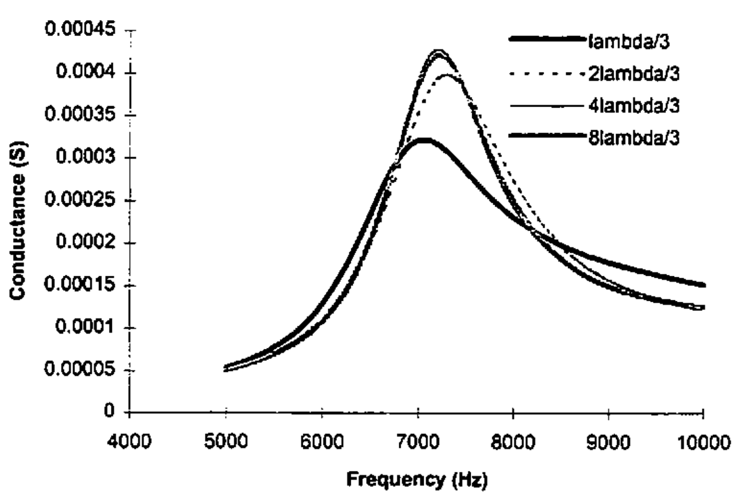

Figure 3; Conductance of one ring in a two ring array, at various array spacings

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A limited experiment has been carried out to measure the conductance of a two ring array, at various projector spacings. Figure 4 compares measurement with modelling predictions at spacings of $\lambda/3$ and $4\lambda/3$. Normalised conductance, with respect to the conductance of a single ring, has been plotted. Good agreement has been achieved at all spacings, although only two spacings have been plotted for clarity.

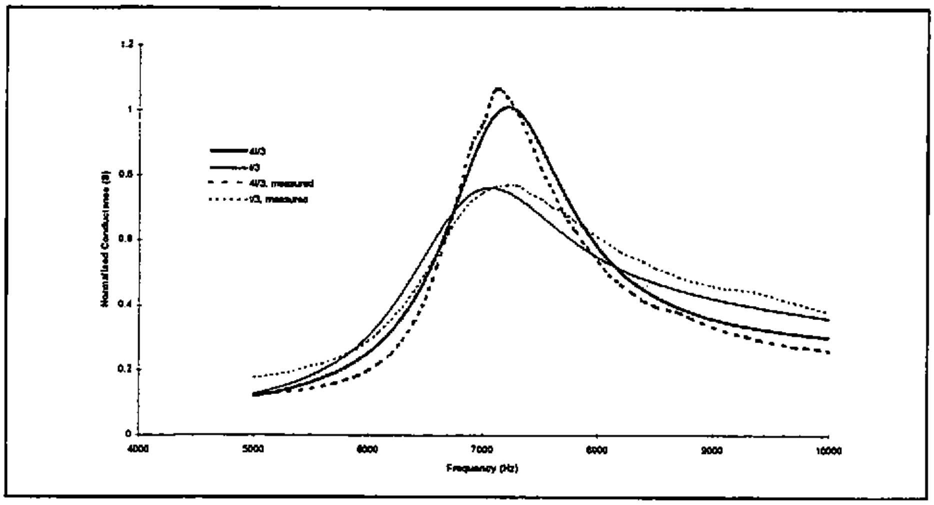

Figure 4; Comparison of measurement with modelling predictions for a two ring array

As extra rings are added to the array, the interaction effects become more pronounced. Inner projectors develop a double resonance in a manner analogous to mode splitting in coupled oscillation systems. Although the amplitude perturbation varies in severity, the higher and lower resonant frequencies and the intermediate trough appear to maintain the same frequency. Some shift in frequency is apparent, but as the devices have a relatively low Q, changes in relative amplitude of the split modes will affect the frequency of maximum conductance. These effects are illustrated in Figures 5 for five ring array. It can be seen that Rings 2 and 3 appear to set up opposing resonance regimes each with a different major resonance.

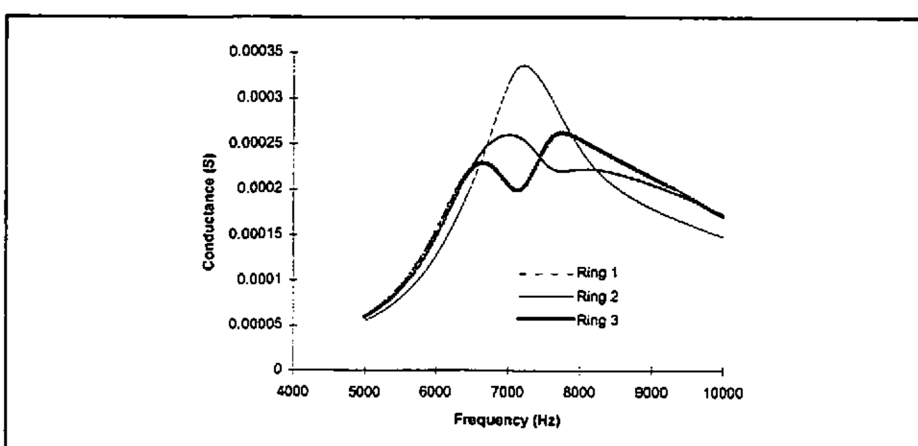

Figure 5; Conductance of a five ring array, spacing = $\lambda/3$

Within the results shown, changes in conductance are relatively benign but conditions can arise in arrays where the conductance of an element becomes negative. Such extremes in electrical performance can lead to failure of the amplifier driving the transducer.

The following results provide an estimate of the change in transducer performance when one element in the array is open circuit. Figures 6 and 7 show the conductance of the remaining transducers in the array. Double resonance effects are again observed although frequency shifts are more variable. Figure 8 shows the effect of accidentally connecting the centre element in reverse polarity. The conductance curves for Rings 1 and 2 are seen to be perturbed in a similar fashion to that seen in Figure 6, but the increased conductance on Ring 2 may become a problem for its power amplifier.

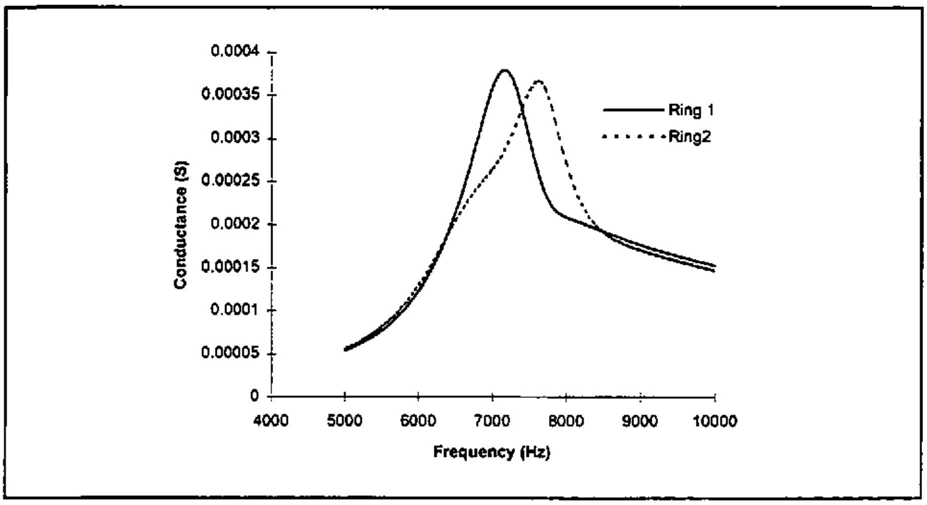

Figure 6; Conductance of a five ring array, Ring 3 (centre ring) open circuit

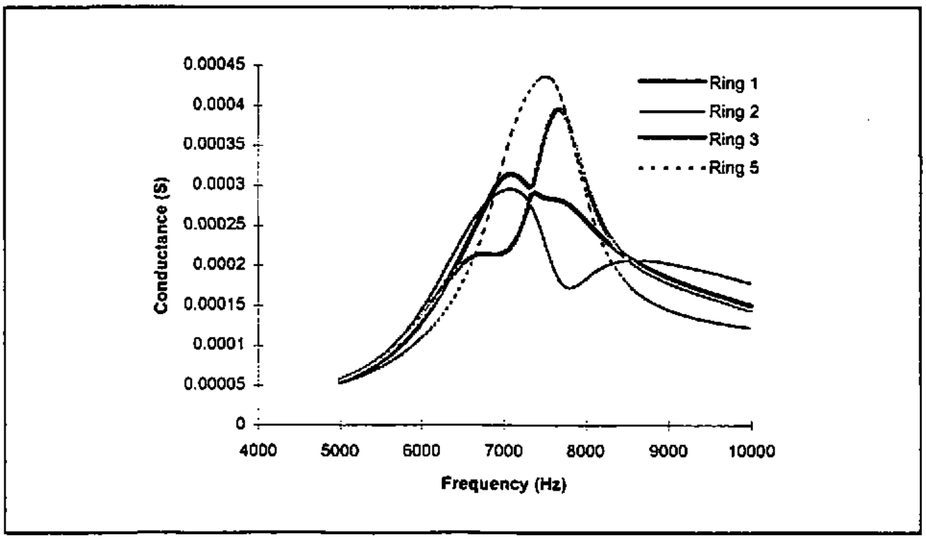

Figure 7; Conductance of a five ring array, Ring 4 open circuit

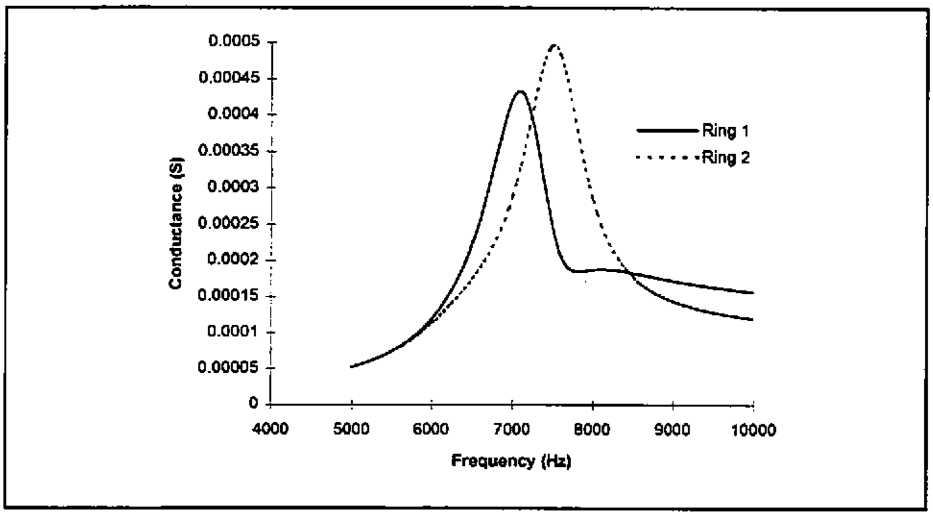

Figure 8; Conductance of a five ring array, Ring 3 (centre ring) driven in reverse phase

The mutual impedance matrices have been calculated over a number of frequencies for the five ring array, using the fully coupled approach in PAFEC. The mutual impedance values of Ring 3 (the central ring) with the other rings in the array are plotted in Figure 9 as a function of frequency. Figure 5 shows how the mutual interaction indicated here is manifest as transducer electrical performance. There is not sufficient information to deduce conductance effects directly from the impedance matrix.

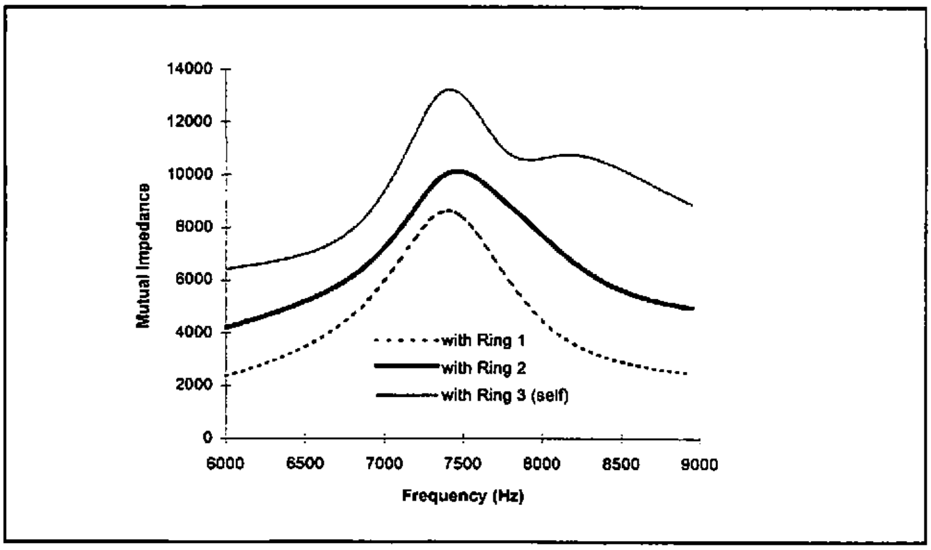

Figure 9; Mutual interaction values of Ring 3 in the five ring array

5. COMMENT AND CONCLUSIONS

The interaction effects between transducers in an array can be modelled using FE and BE techniques. The scope of this study has been restricted to modelling transducer conductance, however it is also possible to observe changes in phase angle, beampattern or even mechanical stresses due to element interaction within the array. These values are important to the sonar designer but to date have often been the subject of guesswork rather than detailed calculation.

The mutual impedance matrix of an array can be calculated. This can provide an estimate of the effect each individual element has on another. It is difficult to ascribe a strict physical meaning to the actual magnitude of the impedance matrix. However in relative terms it is useful for design purposes. Comparing relative sizes of terms within the impedance matrix permits the assessment of the overall interaction between various array configurations. Any pair of transducers that exhibit significant mutual interaction can be identified prior to array construction.

The changes in the electrical response due to array interaction can also be calculated for each transducer, rather than an averaged value for the whole array. This technique can also provide guidance for non-uniform and non-standard spacing and for irregular conditions. It is adaptable to all types of piezoelectric transducers and not limited to the example type used for this paper. It is important to state that the FFRs considered in this paper are heavily damped due to the thick polybutadiene coating. This lowers the efficiency of the FFR and hence reduces the tendency to suffer interaction. For arrays of transducers with higher coupling and lower damping coefficients, much more severe disruption may ensue. Quantifying interaction effects is therefore likely to be of great benefit to sonar array designers providing an estimate of the performance of the elements in an array and determining any danger areas in the design.

6. REFERENCES

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