ADMITTANCE LOOPS AS A TRANSDUCER DESIGNER'S TOOL - MEASUREMENTS AND PREDICTIONS

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1. INTRODUCTION

Measuring the frequency dependent admittance of a piezoelectric transducer is an extremely useful method for analysing the electrical and mechanical properties of the device. Admittance data can be used, with some simplifying assumptions, to calculate the Transmit Voltage Response (TVR), providing an implicit calibration in circumstances when the TVR cannot readily be measured. For small high frequency devices the far-field may be readily encompassed within a tank and the TVR may be measured directly. For large low frequency transducers even very large test tanks cannot provide free-field conditions, so costly sea trials are needed to measure the TVR directly. Here, admittance data offer a cost-effective alternative, either by a much simplified at-sea measurement process or, if sufficiently good admittance measurements can be achieved there, in the tank. This paper considers the assumptions behind the calculation of TVR from admittance and examines the cases for which it is valid.

An essential factor in providing confidence in this approach has been the development and validation of models based on the PAFEC finite element (FE) and boundary element (BE) code to predict the admittance characteristics and TVR of relevant transducers. The paper examines the admittance data of three Free Flooding Ring (FFR) transducers, modelled in this way and measured in the anechoically lined tank at DERA Winfrith. The TVRs calculated from these results are compared with those obtained directly from model and experiment.

2. FFR TRANSDUCERS

Three FFR transducers with different aspect ratios have been investigated. The smallest device is the DERA Test Ring. This has the highest resonant frequency of the FFRs investigated, with a resonance at around 7.5kHz. At this frequency, both admittance characteristics and TVR are easily measured within the tank. The Sparton Ring is the largest device and has the lowest resonant frequency. With a resonance at just below 1kHz, it is not possible to measure the TVR in the restricted environment of the tank. In addition, the admittance loops measured in the tank show spurious features caused by reflections from the tank walls, surface and bottom. The intermediate device is manufactured by Morgan Matroc Ltd. The resonant frequency at around 3.3kHz allows accurate measurements of admittance, however the accuracy of the TVR measurements is questionable.

The DERA Test Ring is made of solid PZT4 piezoceramic, with outer radius 57.15mm, inner radius 50.8mm and axial height 28.0mm. The ring is silvered on the inner and outer surfaces and poled in the radial direction.

The Morgan Matroc design is a fully segmented ring of outer radius 105mm, inner radius 95mm and axial height 70mm. It is constructed from 60 segments of PC4D ceramic (a grade equivalent to PZT4), with pre-stress supplied by a GRP winding. The ceramic is poled in the tangential direction.

The Sparton Ring consists of 40 pairs of flat tangentially poled piezoceramic plates spaced with steel wedges to form the circular shape. The ring assembly is pre-stressed with a kevlar wrap. An external hexagonal support ring is used to mount the finished transducer. The outer radius of the boot is 355.6mm.

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3. ADMITTANCE AND CALCULATION OF TVR

The electrical characteristics of a transducer can be measured by applying a unit voltage across the terminals of the device over a band of frequencies around its resonance and measuring the resulting admittance. The admittance is composed of a real part, the conductance (G), and an imaginary part, the susceptance (B). The admittance is plotted as a vector in the susceptance-conductance plane, with frequency increasing around the loop. The admittance loop shown in Figure 1, below, is for a well-behaved transducer with a clearly defined resonance. Deviations from this idealised curve may be observed because of the effects of other resonances within the frequency band plotted. When damping is very small, the loop approximates to a circle and is generally large. When the transducer is more heavily damped, the admittance loop is smaller and flatter. A more complete discussion of admittance loops is given in [1].

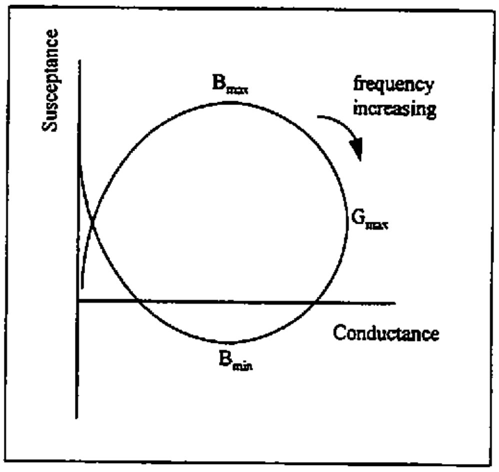

Figure 1: Admittance Loop of a Well-Behaved Transducer

The tank at DERA Winfrith is anechoically lined with dimensions 5m deep, 6m wide and 10m long. Interpretation of the admittance data assumes that energy is radiated into free-field conditions, with no reflections. Conditions close to this are achieved with absorbent linings, usually wedges, on the tank walls and bottom. There is, however, a frequency limit below which the wavelength becomes too long for the lining to act effectively. In addition, the water surface produces backscattering especially for transducers with broad vertical beamwidths. For large low frequency devices, the restricted tank environment leads to reverberation and the accuracy of the measurements made in these conditions is questionable.

In cases where far-field TVR measurements are not possible but there is confidence in the admittance measurements, the TVR can be calculated using admittance data from both in air and in water measurements as follows:

$$\eta_{ma} = (G_{air} - G_{wat}) / G_{air}$$

where η_{ma} is the mechanical-acoustic efficiency and G_{air} and G_{wat} are the maximum motional conductances of the device in air and in water respectively.

$$\eta_{em} = G_{wat} / G_{max}$$

where η_{em} is the electrical-mechanical efficiency and G_{max} is the maximum total conductance of the transducer in water.

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$$\eta_{ea} = \eta_{em}\,\eta_{ma}$$

where η_{ea} is the electro-acoustic efficiency. The TVR may then be calculated as follows:

$$TVR = 10\log_{10}\eta + 10\log_{10}G + DI + 50.8$$

where η is the efficiency, G is the conductance (in Siemens) and DI is the directivity index. The units of TVR are dB re 1Pa/V. The constant term, 50.8, is for sea water and is replaced by 50.5 for measurements in fresh water. Strictly, η, G and DI vary with frequency. In practice, when using the above equation, η and DI are calculated at resonance only and are taken to be constant. The improved modelling capability enables computation of bounds for the error introduced by this simplification, and corrections can be made, if necessary.

4. MODELLING METHOD

The theoretical modelling has been based on the PAFEC FE and BE code [2]. The FE method is used to describe the structure of the ring 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. TVR, admittance data and far-field directivities are calculated from the Helmholtz Solution for a hybrid FE/BE model. The codes have been extensively validated and can essentially enable us to conduct a "numerical experiment". The derived results can therefore be treated as idealised free-field data against which to judge the validity of the actual measurements performed in the tank. More importantly, the admittance and TVR can be calculated separately to assess the suitability of the expression (cited above) used to estimate the TVR from admittance data and assumed constants.

The DERA Test Ring is a radially poled single piece of ceramic and has a perfectly axisymmetric structure, allowing for a simple and efficient axisymmetric model. A simple rectangular generator mesh is created and the ring is taken to be a solid of revolution of the generator mesh about the x-axis. Extensive modelling of the DERA Test Ring, both singly and in arrays has been carried out and further details on the model are available [3, 4].

The larger rings could not be represented by a simple axisymmetric model. Firstly, unlike the single-piece DERA Test Ring, the Sparton Ring and Morgan Matroc FFR are segmented and the devices are not truly axisymmetric. Secondly, the ceramic wedges are tangentially poled and the PAFEC axisymmetric elements do not allow tangential polarisation. Three-dimensional models were therefore required. Within these, it was possible to take advantage of the symmetry of the structures and only wedge sections of the rings were modelled, with symmetries imposed by invoking appropriate boundary conditions. Extensive modelling of segmented rings has been carried out, more detailed descriptions of the models are given elsewhere [5, 6].

5. DERA TEST RING - MEASUREMENTS AND MODELLING

The measured and predicted admittance loops of the DERA Test Ring in air and in the water tank are shown in Figures 2 and 3 respectively. Tables 1 and 2 compare the maximum conductances, minimum and maximum susceptances and the frequencies at which these are achieved. Extremely good agreement is seen between the PAFEC predictions and measurement. The FE/BE model predicts a slightly smaller in air admittance loop than measurement, however the resonant frequency and frequencies at minimum and maximum susceptance have been remarkably well predicted. The magnitude of the admittance in water has been predicted very well, however the frequencies do not show such close agreement.

The magnitudes of the predicted and measured admittance loops agree better in water than in air. In air, the structural damping due to the dielectric loss (tanδ) of the ceramic dominates. This can vary significantly from one transducer to another and from one batch of ceramic to another. In water, the radiation damping due to the presence of the water dominates. This is well described by the PAFEC model.

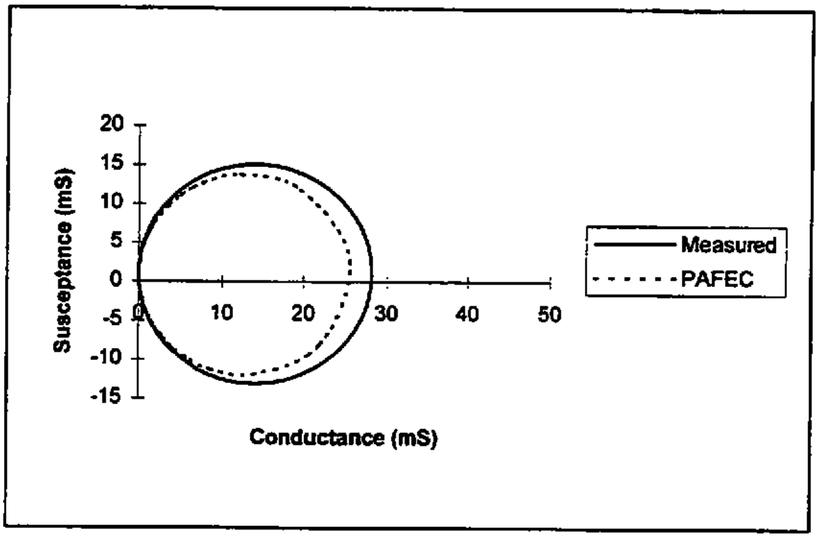

Figure 2: Measured and Predicted Admittance of the DERA Test Ring in Air

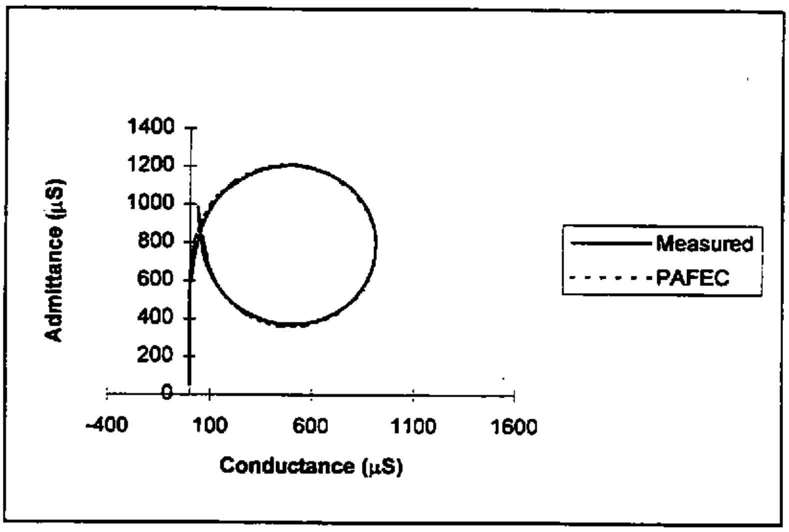

Figure 3: Measured and Predicted Admittance of the DERA Test Ring in Water

	In air					
	f_0 (kHz)	G_{max} (mS)	f_{Bmax} (kHz)	B_{max} (mS)	f_{Bmin} (kHz)	B_{min} (mS)
Measured	9.704	28.14	9.69	15.07	9.719	-13.08
PAFEC	9.71	25.57	9.69	13.8	9.73	-11.9

Table 1: Measured and Predicted Admittance of the DERA Test Ring in Air

	In water					
	f_0 (kHz)	G_{max} (mS)	f_{Bmax} (kHz)	B_{max} (mS)	f_{Bmin} (kHz)	B_{min} (mS)
Measured	7.55	0.908	7.3	1.208	7.9	0.371
PAFEC	7.2	0.9	7.0	1.21	7.6	0.364

Table 2: Measured and Predicted Admittance of the DERA Test Ring in Water

Figure 4 shows the measured TVR and the TVR predicted by the PAFEC model. Again, good agreement is seen between the PAFEC model and experiment. Additionally, the measured admittance data were used to calculate the TVR, as described in Section 3 above. This was also carried out using the PAFEC predicted admittance data, for comparison. The indirect method of calculating TVR from efficiency and conductance data shows good agreement with direct measurement.

In Figure 4, the broadest TVR peaks are seen in the direct measurement and direct calculation of TVR. Above resonance, the direct PAFEC TVR calculation shows closest agreement with measurement. The two TVR curves derived from admittance data are narrower with faster fall-off above resonance. This narrowness may be attributed to the assumption that there is only a single resonance. FFRs rarely exhibit a single pure resonance. Further differences may be due to the assumed constants in the equation used to calculate TVR. In particular, the directivity index (DI) varies below and around the first resonance, becoming more stable at higher frequencies.

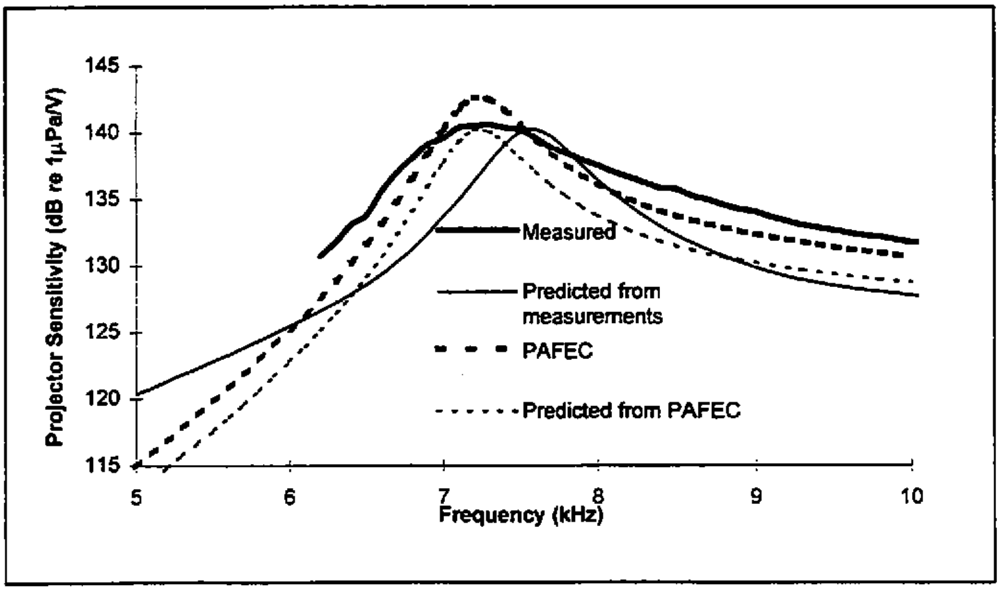

Figure 4: Comparison of Measured and Predicted TVR

The measured admittance and TVR data do not show the same resonant frequency. This is not seen with the data predicted by the model and is therefore attributed to be a manifestation of the experiment. The type of admittance measuring equipment may be a major factor.

6. MORGAN MATROC FFR - MEASUREMENTS

The measured and predicted admittance loops of the Morgan Matroc FFR are shown in air and in water in Figures 5 and 6 respectively. Excellent agreement is achieved between measurement and the FE/BE model predictions. The maximum conductance, minimum and maximum susceptances and the frequencies at which these are achieved are detailed in Table 3. In addition to the main resonance detailed in Table 3, there is a higher resonance seen as a small kink in the admittance loops. In water, the higher resonance occurs at 5.24kHz.

	f_0 (kHz)	G_{max} (mS)	f_{Bmax} (kHz)	B_{max} (mS)	f_{Bmin} (kHz)	B_{min} (mS)
In air	4.425	24.4	4.395	13.11	4.455	-10.79
In water	3.280	2.177	3.160	1.781	3.460	-0.216

Table 3: Measured Admittance of Morgan Matroc FFR in Air and in Water

The free-field measured TVR and the PAFEC predicted TVR are shown in Figure 7. TVR has also been calculated using measured admittance data from the tank and admittance data from the PAFEC model these are also shown in Figure 7. Excellent agreement has been achieved between the four cases. The FE/BE model has predicted a slightly higher TVR and slightly lower resonant frequency than experiment. The diffraction minimum, seen at around 930Hz, has not been accounted for when calculating TVR from admittance data as the DI has been assumed constant in the formula cited in Section 3.

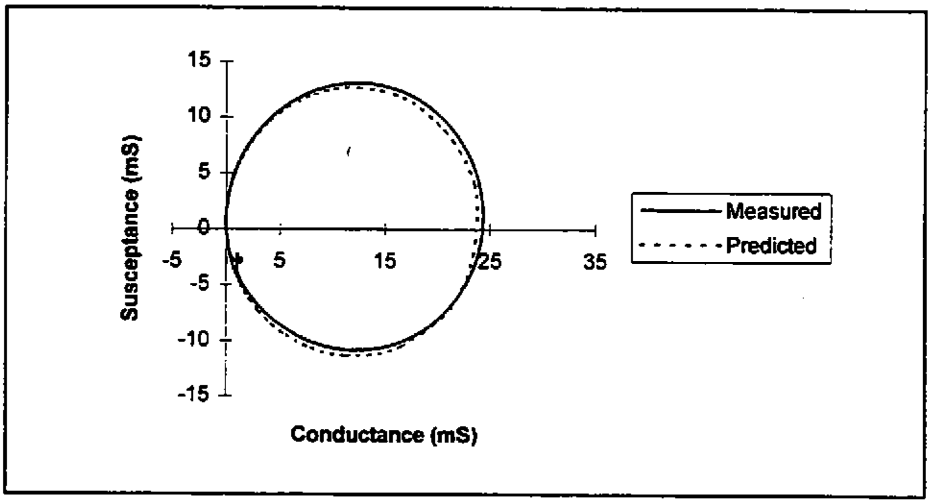

Figure 5: Measured and Predicted Admittance of Morgan Matroc FFR in Air

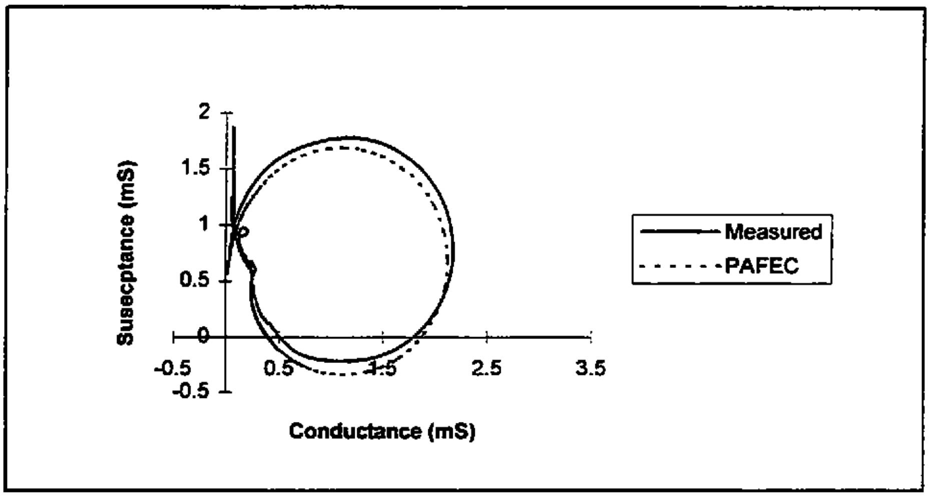

Figure 6: Measured and Predicted Admittance of Morgan Matroc FFR in Water

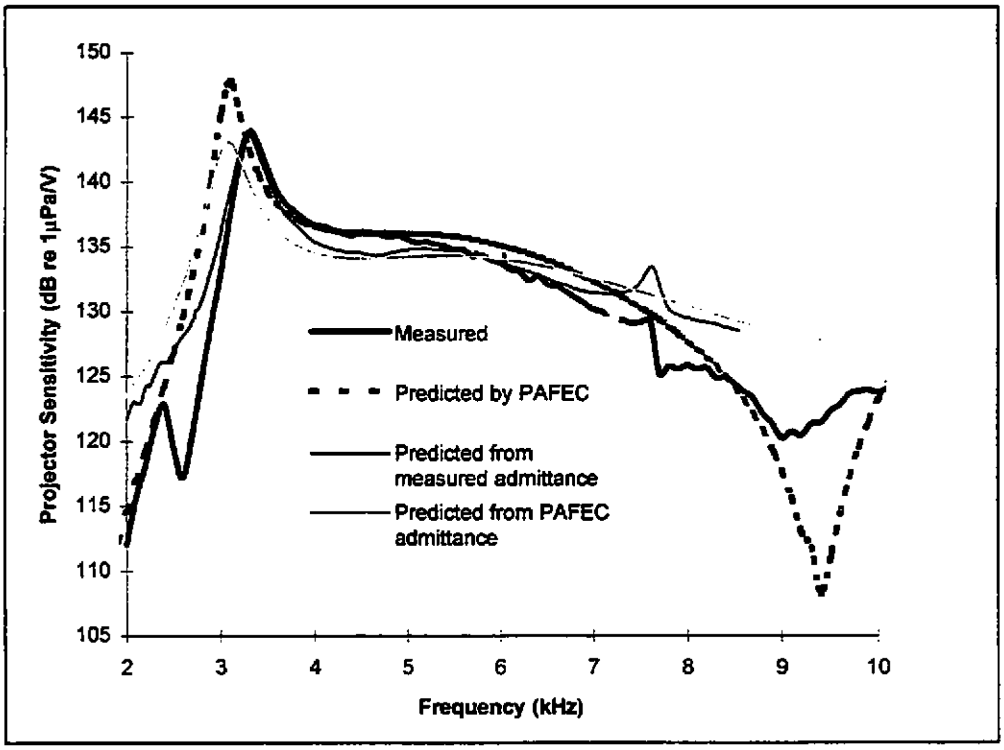

Figure 7: Measured and Predicted TVR of the Morgan Matroc FFR

7. SPARTON RING - MEASUREMENTS AND MODELLING

The Sparton Ring transducer exhibits a low frequency resonance at 950Hz. At this low frequency TVR cannot be accurately measured in the restricted tank environment. Figure 8 shows the admittance loop of a Sparton Ring measured at sea in free-field conditions compared with that measured in the tank at DERA Winfrith. The loops are very different, which indicates that admittance data measured in the tank may not be ideally used to predict TVR. The maximum conductance of the tank and free-field loops do, however, show good agreement.

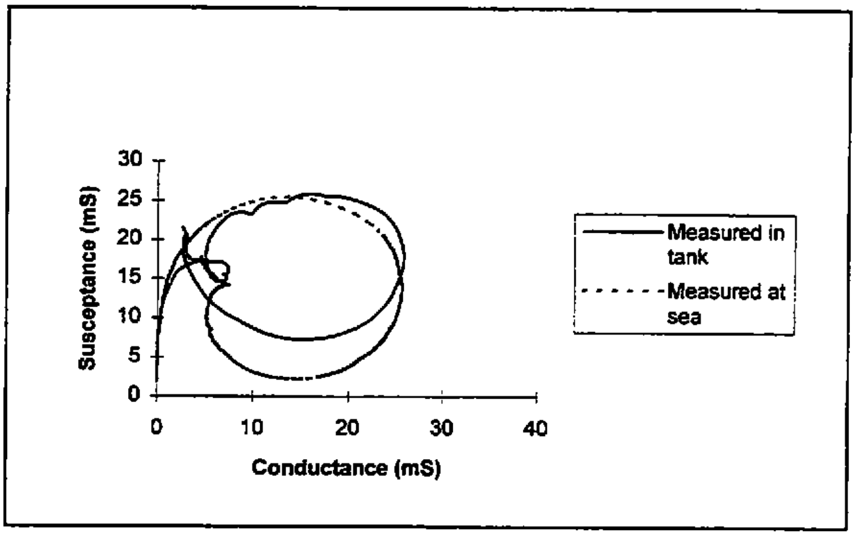

Figure 8: Tank and Free-Field Admittance Measurements of a Sparton FFR

Figure 9 compares the admittance of the Sparton Ring measured in free-field conditions with that predicted by the PAFEC FE/BE model. Extremely good agreement is seen.

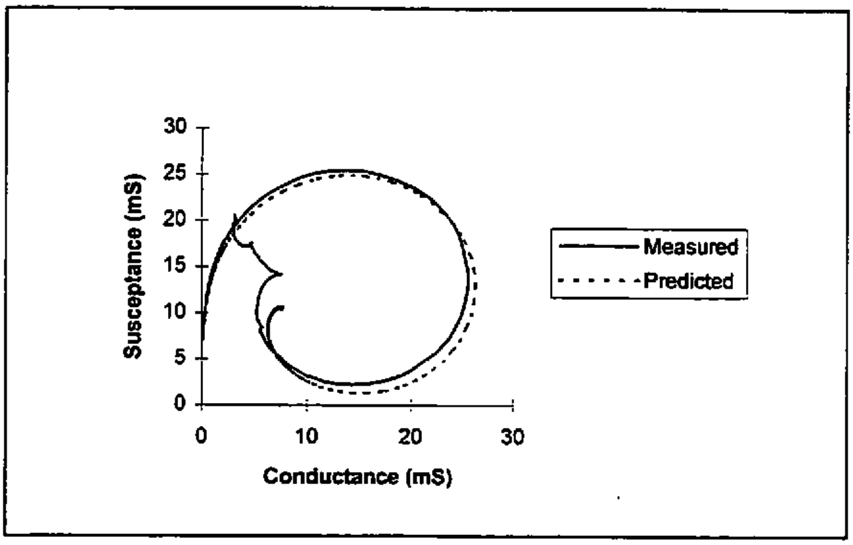

Figure 9: Measured and Predicted Admittance of a Sparton FFR

The admittance data measured in the tank has been combined with in air measurements to predict the TVR of the Sparton Ring, using the equations detailed in Section 3. This is compared in Figure 10 with measured TVR, PAFEC predicted TVR and TVR predicted from measured free-field admittance data and PAFEC admittance data. The TVR derived from tank admittance data shows very poor agreement, as expected. The free-field predicted

TVR shows excellent agreement. The FE/BE model predictions also show very good agreement with experiment, however the FE/BE model has predicted a slightly higher TVR than experiment.

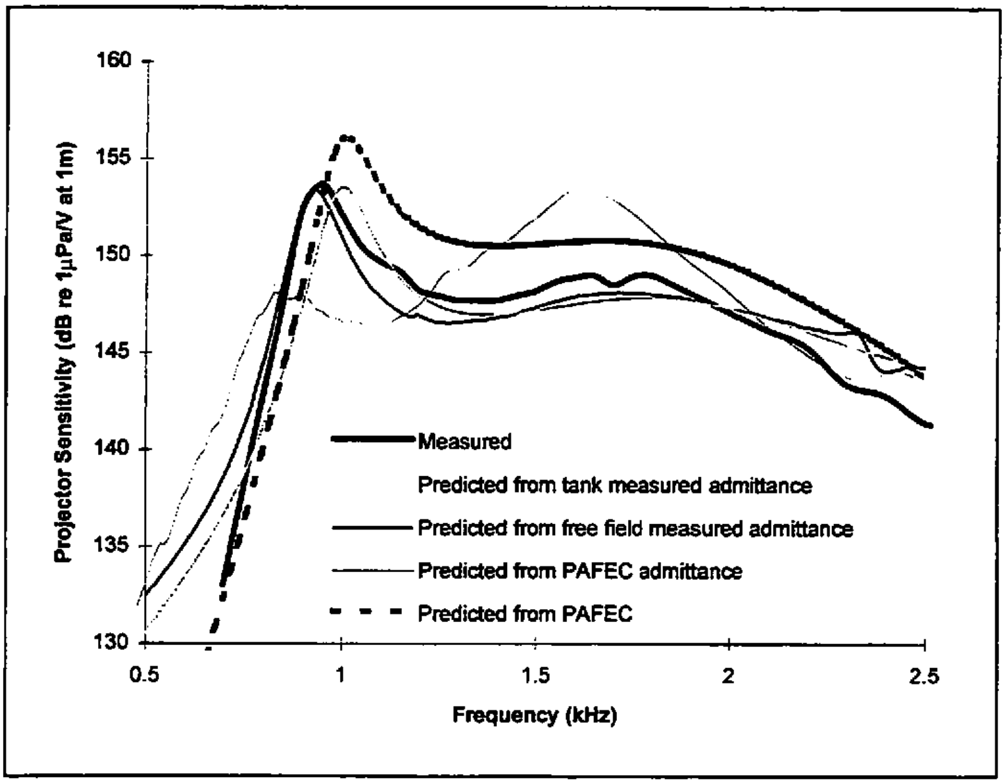

Figure 10: Measured and Predicted TVR of the Sparton Ring

8. CONCLUSIONS AND FURTHER WORK

Examining the dynamic admittance of an electro-acoustic transducer is a very useful design aid. In particular, in some circumstances where it cannot be measured directly, the projector TVR can be estimated from these data. One novel aspect of this work is in verifying this technique using numerically derived results; comparing the directly predicted TVR with its estimate from the admittance. However it is important to understand the assumptions behind, and corresponding limitations of, using the admittance to predict acoustic performance. Applying these ideas to transducers of current interest with relatively wide operating frequency bandwidths, such as FFRs, is challenging and needs careful interpretation and scrutiny of results. When there is sufficient confidence that good admittance data has been derived by measurement, accurate estimates of acoustic performance can be made around a well defined resonance. When extrapolating beyond this limited frequency range some additional information regarding the transducer's efficiency and DI should be sought (supported by the numerical modelling).

Admittance data obtained from measurements in the tank at DERA Winfrith have been shown to provide a good prediction of TVR for the DERA Test Ring and Morgan Matroc FFR. For the low frequency Sparton Ring, the admittance data from tank measurements is insufficiently accurate to give a good prediction of TVR. Sea trials are unavoidable in this instance, but even here the use of admittance data offers considerable simplification and cost reduction. Coupled with the excellent agreement achieved by the PAFEC models, these results demonstrate the potential for further cost-effective improvement in low frequency transducer and array design.

9. REFERENCES

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