A NEAR-FIELD MEASUREMENT SYSTEM TO DETERMINE THE FAR-FIELD RADIATION CHARACTERISTICS OF ARRAYS OF HIGH POWER LOW FREQUENCY SOUND SOURCES

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ABSTRACT

Prediction of the far-field acoustic radiation from transducers and arrays using measurements of the near-field has been accomplished many times in the history of underwater acoustics although the techniques are still not widely used. The purpose of this paper is to discuss the near-field calibration system most recently developed by DERA for an array of low frequency sound sources. The method of determining the far-field radiation characteristics from measurements made in the acoustic near-field, the intricacies of the system, and practical results are discussed in detail.

1. INTRODUCTION

For large aperture arrays the practical difficulties of making direct measurements of the far-field response are considerable. This applies both to receiving arrays where the response of the array to plane waves incident from different directions is sought, and transmitting arrays where the acoustic output from an array in different directions is required. The near-field region (or Fresnel region) of a large transducer or array is often defined as

$$r < L^2/\lambda \tag{1}$$

where L is the aperture of the array and λ the wavelength at the frequency of interest. Within this region, for a wave received from the measurement point the phase differences between the elements of the array are significantly different from those for a plane wave incident from the far-field. Direct measurements within this region therefore do not give an accurate result for the far-field response. In most calibration facilities, placing hydrophones or making transmissions at large distances from the array is impossible due to limitations in the size of the reservoir or water tank in which measurements are undertaken. Measuring the far-field response directly also introduces problems in orientating equipment accurately and avoiding surface reflections and inhomogeneities in the medium over the propagation path. There is therefore considerable interest in calibration techniques which avoid the need for far-field measurements.

The concept of determining the far-field response from measurements taken in the near-field is not new. Methods were developing in the underwater acoustics and electromagnetic research fields in the 1960's. In underwater acoustics, two methods were developed. Trott [1] developed the idea of a Near Field Calibration Array (NFCA) in which the elements of a planar array are shaded to ensure the array acts as a plane wave filter to sources within a finite measurement volume. The shading coefficients for the desired frequency range are determined by an optimization technique. The method has been used successfully at Naval Research Laboratory in the US for many years. Generalisations to steered NFCAs and to non-planar measurement surfaces have been developed [2].

The second method, initially proposed by Horton and Innis [3], is based on an integral representation (derived from Green's Theorem) for the acoustic field exterior to a closed measurement surface surrounding the array. The method in general requires knowledge of the pressure on the surface and the normal derivative

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of the pressure, and a Green's Function which is a solution to the wave equation with a point source at the point at which the far-field is required. For some measurement surface geometries, a Green's function which vanishes on the measurement surface is available, and the integral representation can then be reduced to a form which involves only pressure. The far-field pressure can be calculated by measuring the near-field pressure at a number of points over the measurement surface, evaluating the Green's Function, and performing the integration numerically. A discussion of the spatial sampling of the measurement surface that is required and the effect of errors in the measurement of near-field pressures has been presented by Earwicker [4]. Equivalent near-field calibration techniques have been developed for electromagnetic antennas [5] and [6].

In this paper, the theoretical basis of the near-field calibration technique used is explained. The practical difficulties that were overcome in the construction of the system are discussed. Some results showing the use of the system for the calibration of an array of low frequency sound sources are presented.

2. THEORY

The integral representation method has been adopted in the work reported here. The pressure, *p(x)*, at a point exterior to a measurement surface *S* can be expressed in terms of the following integral

$$p(x') = \frac{1}{4\pi}\int_S (p(x)\nabla G(x,x') - G(x,x')\nabla p)\,\mathbf{n}\,dS \tag{2}$$

where $\mathbf{n}$ is the outward normal. The Green's Function, $G(x,x')$, must satisfy the inhomogeneous wave equation with a point source at $x=x'$, a radiation condition at infinity, and the boundary condition on the measurement surface. It is only for cylindrical and spherical surfaces that convenient expressions for the Green's Function are available.

In the near-field calibration system described here a spherical near-field measurement surface has been used. Cylindrical surfaces have been used in other systems developed by DERA, but the spherical surface was considered the most appropriate for the arrays to be calibrated and for measuring the response in all directions. Use of a cylindrical surface requires the contribution to the integral representation from the end caps of the cylinder to be neglected, which can lead to significant inaccuracies at low frequencies or when the response in the axial direction is required.

For a spherical surface, the Green's Function is, for $r'>r$, given by

$$G(x,x') = -ik\sum_{n=0}^{\infty}(2n+1)\,[h_n^{(2)}(kr')\,j_n(kr) + a_n h_n^{(2)}(kr')]\,P_n(\cos\theta'') \tag{3}$$

where $k=\omega/c$, $\cos\theta''=x.x'$ (the angle between the measurement point and the far-field direction), ω and c are the radian frequency and wave speed considered, a_n is a coefficient which depends on ka and kr', and a factor $exp(i\omega t)$ has been assumed and suppressed throughout. Using the asymptotic form of the spherical Hankel function, the following result is obtained

$$p(x') = \frac{\exp(-ikr')}{4\pi a^2 kr'}\int_S p(x)\left(\sum_{n=0}^{\infty}\frac{(2n+1)\,i^{n+1}P_n(\cos\theta'')}{h_n^{(2)}(ka)}\right)dS \tag{4}$$

The integral is a two dimensional integral over the surface of the sphere for each far-field direction.

3. DESIGN OF THE RIG

The calibration procedure involves the measurement of the pressures from the array at a sufficiently closely spaced set of points on the measurement surface, and the calculation of the far-field response by a numerical evaluation of equation (4). In this work, the pressures were measured using a near-field rig which consisted of a number of hydrophones suspended on circular arms which ran along lines of longitude on the spherical surface. The arms were fixed to a central framework which also supported the array under calibration. The hydrophones must be designed to measure the free-field pressure. They must therefore be omnidirectional at the frequencies considered, and interaction effects between the hydrophones and the arms and the neighbouring hydrophones must be minimised. They must also be insensitive to vibrations of the arms excited by the acoustic projectors in the array.

The results presented here are for a vertical line array of projectors which were omnidirectional in the horizontal plane and were mounted in the centre of the rig. The acoustic field is therefore symmetric about the vertical axis of the near-field rig. Consequently measurements on only one circumferential arm were required which greatly simplified the data that needed to be taken and the amount of processing required to calculate the far-field response. However, this type of rig has been used successfully for other arrays (volumetric configurations) where axial symmetry does not hold and measurements on a number of longitudinal arms are required.

Previous work on cylindrical near-field rigs [4] has indicated that the spacing of hydrophones required is very dependent on the acoustic field to be measured. Typically, a spacing of a half wavelength at the highest frequency considered is needed, but for array beampatterns which are highly directional in either the horizontal or the vertical plane a closer spacing may be required. The approach adopted here was to assess the adequacy of the spacings proposed by calculating the far-field response of theoretical arrays similar to the arrays to be tested, from theoretical values for the pressure at the near-field measurement points. This also served as a check on the numerical calculation. The actual response of the arrays may be somewhat different due to a variety of effects (mismatches between the elements or interaction effects) but the assessment of the sample spacing required is expected to be valid. An arm with 36 equally spaced elements was assessed to be sufficient to determine the beampattern of a four ring array for frequencies up to 2kHz, see Figure 1.

The amplitude and phase of the pressures at the near-field measurement positions were measured and stored for each drive configuration (frequency and steer angle) of the projector array. The far-field response was then calculated off-line. The numerical calculation of the response in all directions for each set of data took a few seconds.

4. DATA COLLECTION TECHNIQUE

Figure 2 shows a block diagram of the data collection equipment. The frequency at which the beampattern is to be measured is manually entered into the oscillator and the power amp is adjusted to give the required source level. The transmit signal was typically a 10ms pulse. The 36 hydrophone signals are fed to a DERA designed Analogue to Digital Convertor, where they are digitised and read by the computer. Software was written to simultaneously average the signal received on each hydrophone, typically over 20 pulses. The averaged amplitude and phase data are resolved into a complex pair. These data are used as an input to the beampattern calculation program.

5. MINI NEAR-FIELD RIG

To test the theory and the software a small scale near-field rig was constructed, Figure 3. The 16 measurement hydrophones were initially 25mm ball hydrophones, but these air filled spheres were found to be too large and interaction effects were observed causing a disruption of the field that they were trying to measure. These 16 hydrophones were replaced with much smaller ceramic block hydrophones. These hydrophones required integrated pre-amplifiers, because the capacitance of the cable is a significant fraction of the capacitance of the ceramic block. The hydrophones were mounted onto the near-field rig using soft polybutadeine mounts, which were found to be effective in preventing sound transmission through the body of the rig. The transmit array consisted of 115 mm diameter ceramic rings coated in polybutadeine. Up to four rings could be tested in the mini rig with $\lambda/2$ spacing in between the rings. Figure 4 shows the measured beampattern obtained using the mini near-field rig on an array of two ceramic rings. The measured beampattern was in very good agreement with the classical predicted beampattern. Some endfire effects were observed which were not predicted by the theoretical model.

6. FULL SCALE NEAR-FIELD CALIBRATION SYSTEM

Figure 5 introduces the full scale near-field rig. The measurement hydrophones were end capped cylinders, each with its own pre-amplifier and cable driver designed for the transmission of signals through 200m of cable. The hydrophone was designed with a resilient mount included in the moulding to de-couple the hydrophone from the near-field rig. Figure 6 shows a typical measurement made using the near-field rig with the array deployed to a nominal depth of 100m. The measured beampattern in the main beam direction is in very good agreement with a prediction made using the finite element method and with a theoretical prediction based upon ring theory developed by Sherman & Parke [7]. There are still sidelobes in the endfire directions at 0^{o} and 180^{o} which are not predicted by the theoretical model, however the finite element model does predict some energy radiation at angles close to endfire.

7. FURTHER USE OF NEAR-FIELD MEASUREMENT SYSTEMS

It is hoped that in the DERA, the usage of near-field rigs can be increased, both in tank facilities and at major calibration sites such as the Loch Goil Calibration Facility, where a near-field rig could be permanently set up and available for use. It is also envisaged that the near-field theory can be used to predict the Target Echo Strength of large scale targets where it is not feasible to make measurements in the far field.

8. CONCLUSIONS

The near-field rig provides a measurement system which overcame the problems associated with making far-field measurements on large aperture arrays in limited water depths. The mini near-field rig has possible uses in laboratory acoustic tanks whilst the full-scale near-field rig offers potential measurement capabilities in larger bodies of water but without the need for expensive sea trials in which measurements are made directly in the far field.

9. REFERENCES

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10. FIGURES

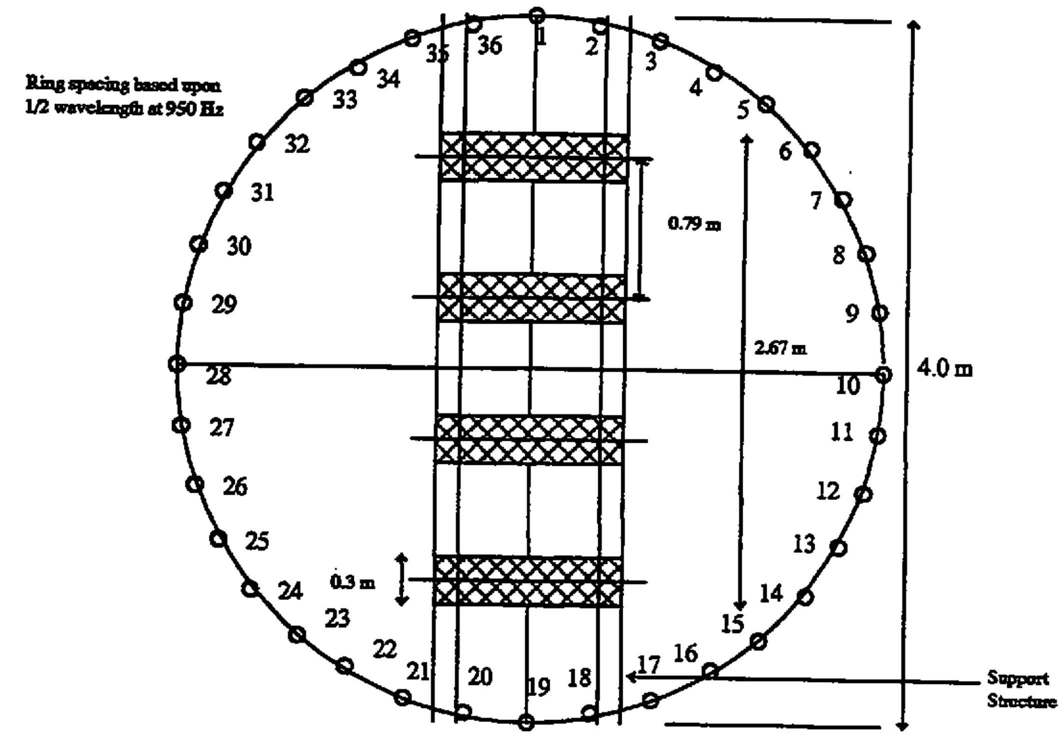

FIGURE 1 SCHEMATIC OF NEAR-FIELD RIG

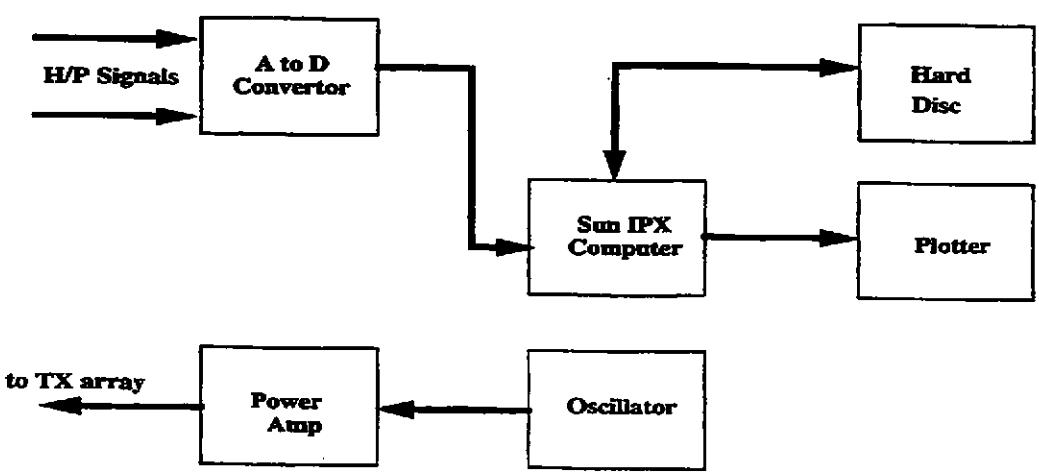

FIGURE 2 BLOCK DIAGRAM OF ANALYSIS SYSTEM

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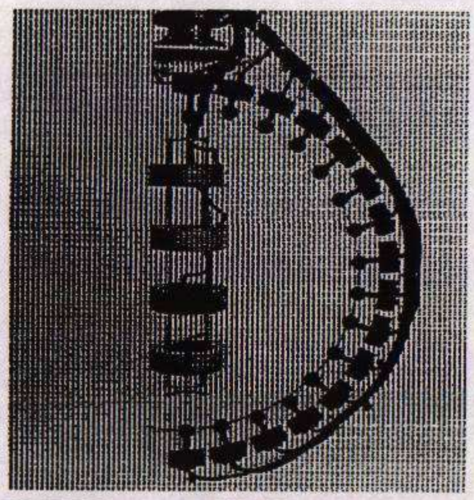

FIGURE 3 MINI NEAR-FIELD RIG

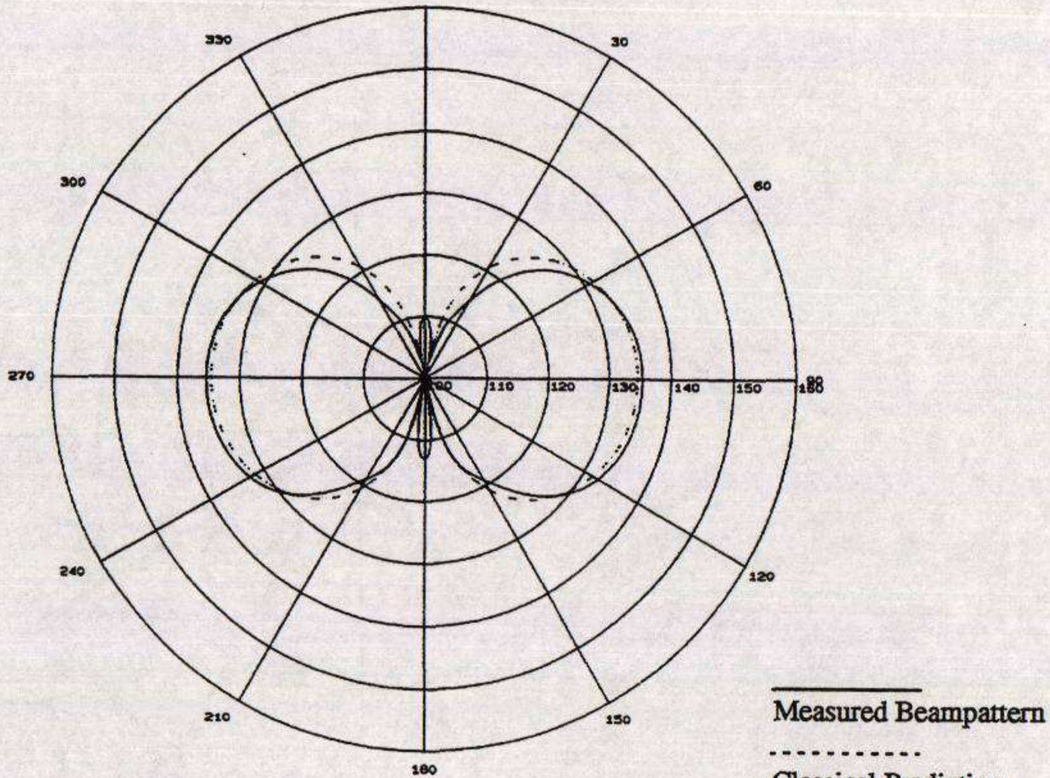

FIGURE 4 RESULTS FROM MINI NEAR-FIELD RIG

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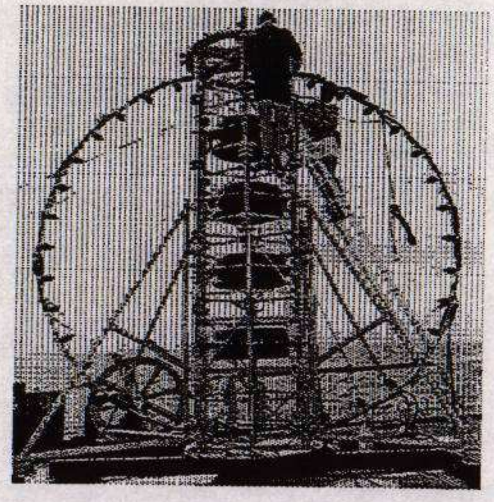

FIGURE 5 FULL SCALE NEAR-FIELD RIG

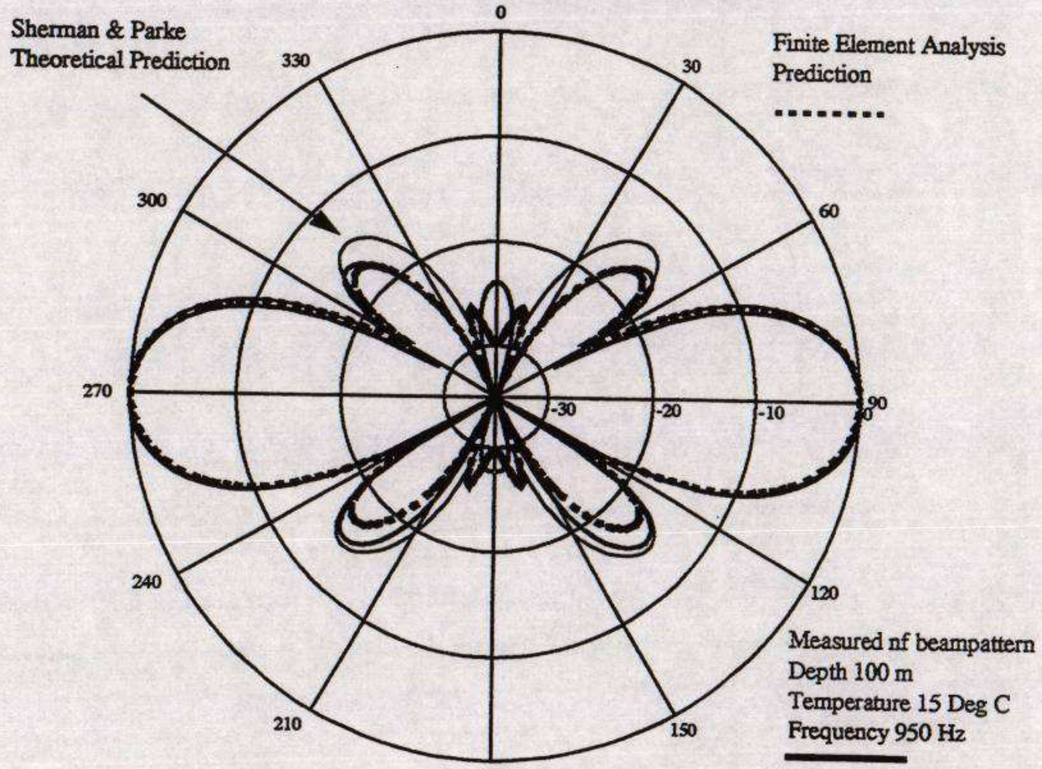

FIGURE 6 RESULTS FROM FULL SCALE RIG

VECTOR HYDROPHONE CALIBRATION TECHNIQUES.

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As part of DERA's Corporate Transducer Programme hydrophones are being developed to detect the vector component of the acoustic wave. These hydrophones have intrinsic directivity despite small dimensions. The standard technique for calibrating vector hydrophones, comparison with a standard pressure sensor, exploits the simple, proportional relationship between the particle velocity and pressure perturbations caused by travelling plane waves. In practise, these conditions are approximated by working in the distant far-field of a finite sound source. Close to the source, the velocity field, in particular, contains significant contributions due to evanescent waves, and the simple relationship between velocity and pressure is no longer applicable. Failure to meet the stringent far-field conditions required for this simple method of calibration can significantly reduce the accuracy of measurements carried out in a confined environment such as a water tank.Three vector hydrophone calibration techniques are currently being developed at DERA Winfrith which will produce accurate results without the need for a large separation between source and hydrophone. These are: a travelling wave tube, a projector array tuned to produce a quasi-plane wave near-field over an extended volume, and a near-field holography method. This paper contains a brief description of the vector hydrophones and the three calibration methods, outlining the merits and limitations of each technique.