PLANE/CYLINDRICAL WAVE SYNTHESIS IN A SMALL TANK APPLIED TO FAR-FIELD BEAM PATTERN MEASUREMENT OF A 300KHZ SONAR TRANSDUCER

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Abstract: *It is highly desirable to infer far-field behaviour of a radio antenna or SONAR transducer, from near-field measurements. This approach allows the measurements to be made in a small tank (or anechoic chamber), under controlled conditions at a fraction of the cost of the equivalent free-field procedure. One of the techniques available is to generate a plane wave in order to create far-field conditions at the transducer under test (TUT). The equipment required is often referred to as a Plane Wave Converter in the field of radio communications, or the Trott Array in underwater acoustics. In essence, the plane wave is synthesised by a 2-D array of point sources which, acting together, generate a plane wave according to the Huygens Wavelet principle. The 2-D array can be reduced to a line-array for a TUT with large aspect ratio, in which case a cylindrical wave is generated. A common criterion in the design of the array is that the Huygens element spacing should be less than four fifths of the wavelength. Applying this principle to the beam pattern measurement of the of a 300kHz SONAR transducer of length 108 wavelengths, would require an array at least 135 Huygens elements wide, in order to generate a uniform wave of the same dimensions. This would clearly require a significant investment, and is the reason that this method is usually applied at lower frequencies. An alternative implementation that is studied in this article, is to scan a single Huygens element mechanically. This allows the array to be composed of any number of elements. The spherical wavelets thus generated, when summed at the receiver, are equivalent to simultaneous transmission with multiple sources, and therefore indistinguishable from a plane (or cylindrical) wave. The transducer tested has a far-field distance of 58m, but the measurements presented were taken at only 67cm from the transducer (well in the near-field). The resulting horizontal beam pattern compares favourably with the calculated far-field pattern for a rectangular aperture.*

Keywords: *Plane wave, Cylindrical wave, Near-field, Beam pattern, Antenna, Transducer, Acoustic measurement, Superposition, Huygens*

1. INTRODUCTION

Ideally, measurement of transducer radiation patterns is carried out in the far-field. This is the region where spherical spreading occurs, with pressure falling off as the reciprocal of range and the beam pattern becoming independent of range from the transducer. A conservative estimate of the far-field distance is given by [1]:

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

Where r is the far-field distance, L is the length of the transducer and λ is the wavelength.

The transducer under test (TUT) characterised in this article has a horizontal aperture of 108λ at 300kHz, which results in a far-field distance of approximately 58m. Even if such a facility were available, successful practical implementation would rely on a high degree of stability between transmitter and receiver due to the highly directional beam patterns which are a consequence of multi-wavelength apertures.

Alternative, near-field measurement techniques fall largely into two categories; the Helmholtz-Kirchhoff integral (DRL) and the Plane Wave Generation (PWG) methods [2].

In the PWG case, a plane wave is generated by an array of point sources, according to the classical Huygens wavelet concept. The plane wavefront, incident on the transducer to be tested allows measurement of the receivers' far-field characteristics. In the field of underwater acoustics these planar near-field calibration arrays are often referred to Trott arrays after their inventor [3]. Equivalent systems in the field of radio communications are referred to as plane wave converters (PWC) and are available commercially [4].

The generated wavefront can be represented by a summation of point sources (figure 1):

$$p(x_m, y_m, z_m) = \sum_{n=1}^{N} a_n \exp(-\mathrm{i}\phi_n) \exp(-ikR_{mn})/R_{mn} \tag{2}$$

Where: $p(x_m, y_m, z_m)$ is the pressure at field point x_m, y_m, z_m , at range R_{mn} due to N point sources arranged on a plane, a_n and ϕ_n are the amplitude and phase weightings of the n^{th} source and k is the wavenumber (the time dependence term $\exp(i\omega t)$ has been omitted).

Ideally, the spacing of the point sources should be no greater than $0.8\,\lambda$ [2] in order to generate a uniform plane wave. This criterion can be difficult to achieve at short wavelengths, due to the expense and complexity that a large planar array with densely packed grid of sensors would imply. Furthermore, closely spaced elements ($<\lambda$) are more likely to suffer mutual coupling [1] thereby invalidating the isotropic point source approximation. For these reasons, the problem of how to optimise a_n and ϕ_n to provide an acceptable plane wave, over a specified volume for a minimum number of elements (N) has received much attention in the literature (for example [5]).

Scanning the point source mechanically obviates many of these issues, allowing parameterisation of the geometry of the planar array of point sources. Each position produces a series of spherical waves, which by the principle of superposition can be summed offline to produce the virtual plane wave.

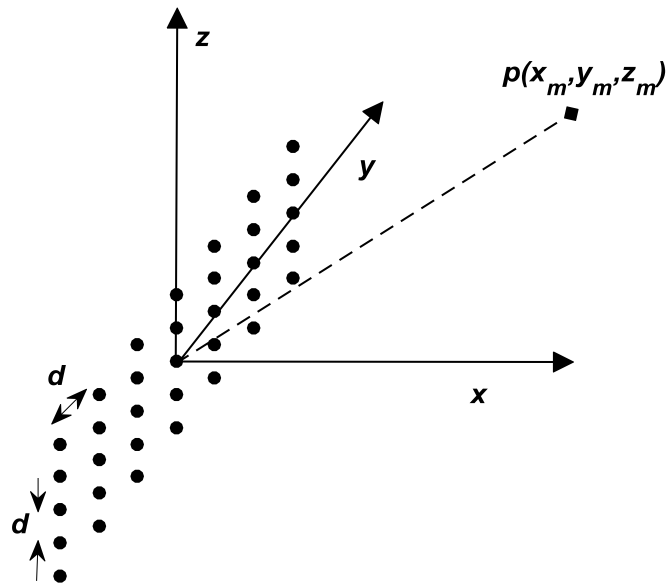

Fig.1: Geometry of the simulated plane wave showing N point sources spaced at d, arranged in a 2-dimensional grid

2. PLANE WAVE GENERATION METHOD APPLIED TO THE TRANSDUCER UNDER TEST

The TUT is a rectangular 300kHz SONAR receiver consisting of 16 elements with overall dimensions of 50mm x 533mm (approximately 10λ x 108λ). Ideally, in order to recreate far-field conditions, the face of the transducer should be insonfied by a uniform plane wave. Numerical evaluation of equation 2 at 300kHz using N = 51000 (340 columns x 150 rows), spacing d=2mm, at a range of 0.65m, Tukey amplitude shading and no phase shading is shown in figure 2. The predicted variation of sound pressure over the face of the transducer is ±0.5dB.

However, application of equation (1) to the relatively small vertical dimension of the TUT suggests that PWG can be replaced by a cylindrical wave generator (CWG), since the curvature of the field in the vertical direction will have no effect on the response of the TUT. This increases the speed of the measurement considerably since the plane array of point sources can be replaced by a line array.

3. SOUND FIELD PREDICTION

A plot of equation (2) for a single line of 340 point sources spaced at 2mm with no phase shading, with and without amplitude (a_n) shading is plotted in figure 3. The spacing used in the calculation (less that that required by 0.8 λ criterion) was chosen to extend the measurement range beyond 300kHz.

Choice of suitable amplitude shading window was based on uniformity of the generated field (in amplitude and phase) and also the scanned length required in order to insonify the TUT over

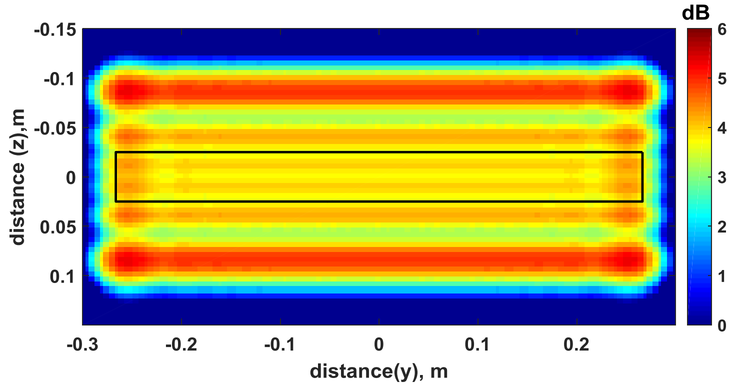

Fig.2: Vertical slice representing the predicted relative SPL at a range of 0.65m from the 2-D array of point sources. The rectangle indicates the outline of the TUT

its entire length. The 2dB variation between 500mm and 800mm range from the CWG is due to cylindrical spreading. Suitability of the Tukey shading was further assessed by calculating amplitude ratio and phase difference of the predicted field to that of an ideal plane wave (figure 4). Variation in amplitude along the line representing the TUT position is <1dB, whereas phase variation is approximately ± 2°.

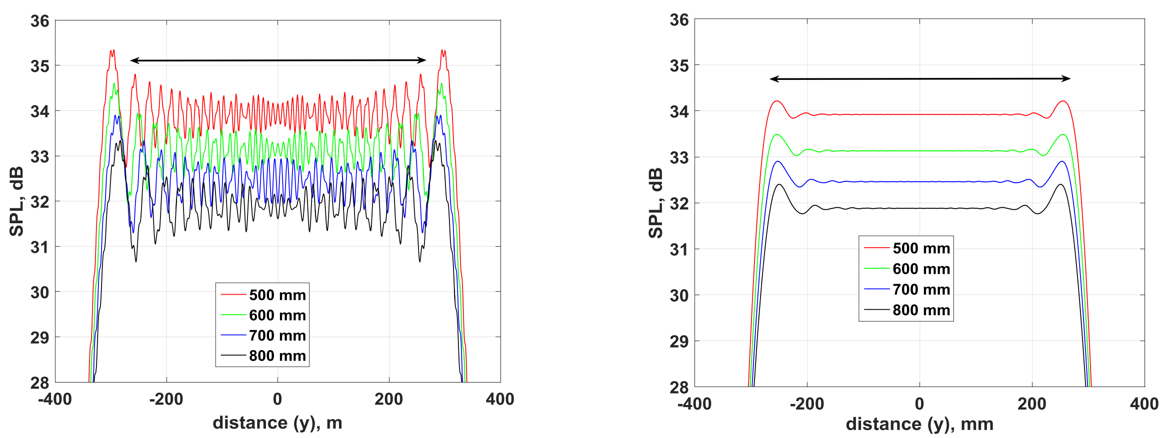

Fig.3: Equation 2 plotted for a single line of 340 point sources spaced at 2mm, for 4 different ranges: Left (no shading), Right (Tukey, 20%), The black arrow indicates the horizontal extent of the TUT

4. EXPERIMENTAL SETUP AND PROCESSING OF ACQUIRED DATA

The 'point' source used to implement the CWG was as a commercially available hydrophone/transducer (Reson TC4034), which at 300kHz is omnidirectional to within ±1.5dB.

The mechanical frame was made of commercially available 45x90mm cross section aluminium struts with transmitter side (scanning probe) and receiver side (TUT) bolted together for extra rigidity. The mechanical frame resulted in a source/TUT separation of around 0.68m.

The transmitted signal was a 200μs pulse centred on 300kHz. Measurements were taken at 340 positions in 2mm increments in the Y (horizontal) direction. For each position, the TUT's 16 channels were acquired, and beam pattern calculated by applying time delay beamforming to the data.

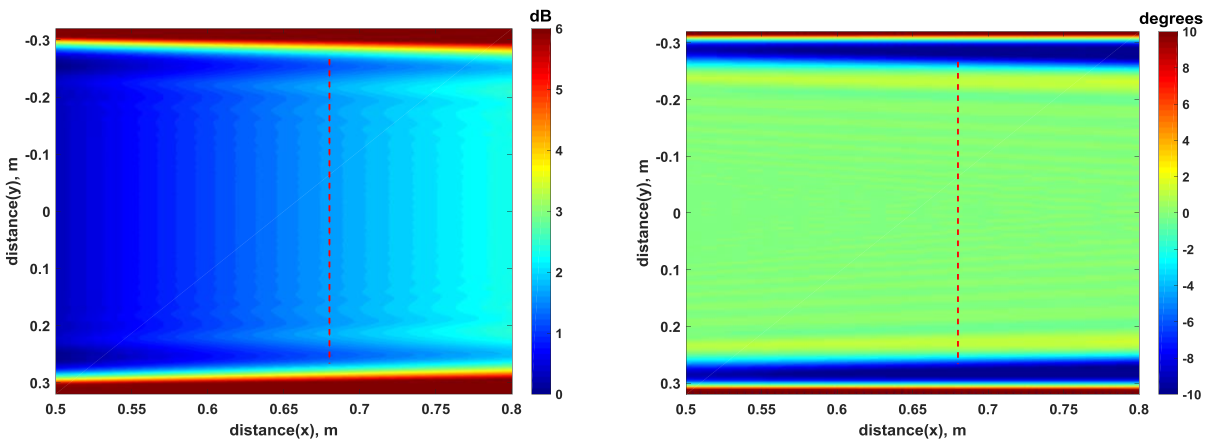

Fig. 4. Comparison of the generated cylindrical wave (Tukey shaded 340 point sources at 2mm spacing) with an ideal plane wave: Amplitude Ratio (Left) and Phase difference (Right). Position of the TUT is shown by the dotted line.

5. RESULTS

The beamformed measurements together with the analytic expression for a rectangular transducer [1] are plotted in figure 5. The main lobe of the analytic expression is followed to a good degree of accuracy by the measurements, and the predicted beam width of 0.47° is accurately determined. Positions of the sidelobes are also well reproduced, although the actual levels to a lesser extent. Depth of the nulls is also variable. Discrepancies can most probably be attributed to TUT element tolerances, TUT inter element couplings and positioning tolerances of the mechanically scanned point source.

6. CONCLUSIONS

Near-field measurement methods provide a practical alternative to far-field characterisation of SONAR transducers and RF antennas, as can be testified by the substantial number of publications on the topic, as well as availability of commercial equipment to perform these measurements.

However, the significant expense and complexity of near-field measurement arrays can act as a deterrent when evaluating other measurements options available. Replacement of the array with a mechanically scanned probe introduces many advantages; including equipment cost savings, increased spatial resolution and elimination of inter element couplings. Automation of the measurement process is straightforward and mitigates the disadvantage the longer measurement time required.

The measurement time can be reduced further by replacing the 2-D rectangular mechanical scan (producing a plane wave) to a linear scan (producing a cylindrical wave). This approximation is valid for transducers of high aspect ratio such as the unit characterised in this article.

Generation of a cylindrical wavefront allowed measurement of the beam width (0.47°) of a 300kHz SONAR transducer, 108λ in length in a small calibration tank, at a distance of only 67cm. The equivalent far-field measurement distance requirement would have been > 50m.

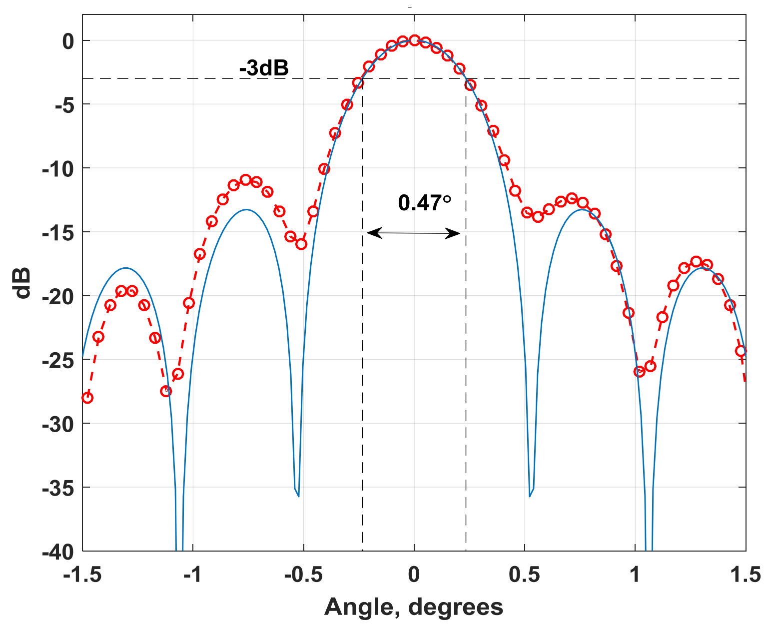

Fig. 5. TUT horizontal beam pattern at 300kHz: Beamformed results (red circles) plotted together with analytic expression for a rectangular transducer.

REFERENCES

1. C. H. Sherman, J.L. Butler, Transducers and Arrays for Underwater Sound, Springer, 2007
2. R.J. Bobber, Underwater Electroacoustic Measurements, Naval Research Laboratory, US Government Printing Office, Washington DC, 1970
3. W.J. Trott, Underwater Sound Transducer Calibration from Near Field Data, J. Acoust. Soc. Am., vol. 36, pp. 1557-1568, Aug. 1964.
4. R.C. Rowell, A Tankielun, Plane Wave Converter for 5G Massive MIMO Basestation Measurements, 12th European Conference on Antennas and Propagation, EuCAP 2018, London, United Kingdom.
5. O.M. Bucci, M.D. Migliore, G. Panariello, D. Pinchera, Plane-wave generators: Design Guidelines, Achievable Performances and Effective Synthesis, IEEE Transactions on Antennas and Propagation, vol. 61, no. 4, pp. 2005–2018, April 2013