The Design of a Transmitter with a Parabolic Conical Reflector for a Sonar Ring

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Abstract

Sonar rings are composed of many ultrasonic receivers arranged in a ring and have in the past used many transmitters. The transmitters have been fired either serially or together and the receivers measure time-of-flight to reflectors in the environment. Serial transmission reduces the measurement rate around the entire ring, whilst parallel transmission incurs interference problems between neighbouring transmitters. This paper describes a new design employing a single high powered transmitter available from Murata (ESTD01 Super Tweeter) and a parabolic conical reflector that overcomes both these issues. The reflector is designed to narrow the vertical beamwidth of the transmitter and to provide good dispersion of the sound around the ring. The paper details the design, TLM simulation and measurements that characterise the performance, such as the intensity compared to previous systems, the elevation beamwidth and the pulse shape.

1 Introduction

SONAR (SOund NAvigation and Ranging) is a popular low cost sensor for mobile robotics. A sonar ring is a circular array of sonar trasducers, typically containing 24 Polaroid ranging modules spaced every 15 degrees. To avoid interference between difference ranging modules different transmitter scheduling policies have been proposed [Borenstein and Koren, 1992]. Simultaneous firing of arrays of transmitters has also been deployed [Yata et al 1999, Fazli and Kleeman 2006] and signal processing can be used to filter interference effects. For example in [Fazli and Kleeman 2006] different transmitted pulse shapes between neighbouring transmitters combined with receiver discrimination can be used to reduce interference. In using many discrete transmitters, inevitably there will be acoustic interference patterns developed when simultaneous transmission is used. Moreover the pulse shape and amplitude versus angle around the ring will vary due to the acoustic interference and due to the variation within the beamwidth of each discrete transmitter. The other issue facing sonar ring designers is the elevation beamwidth. To avoid spurious echoes from the floor, such as small steps associated with room entrances and floor boards, it is desirable to have a narrow vertical beamwidth in the transmitter. Using round transmitters, such as the Polaroid 7000 and instrument grade transducers results in a vertical beamwidth equal to the horizontal where one is desired to be minimised and the other maximised. This paper proposes a new approach to solve these problems using a single commercially available tweeter combined with a custom designed parabolic conical reflector.

The paper is organised as follows. The parabolic reflector design is discussed and then a simulation model based on an acoustic TLM (Transmission Line Matrix) model is introduced for an axial symmetric acoustic environment and results shown for the parabolic reflector design. The hardware implementation is then discussed and finally experimental results are presented quantifying the beamwidth versus vertical angle, the variation of pulse shape around the ring and the intensity of the transmission compared to conventional systems. Finally conclusions and future design options are discussed for the sonar ring.

2 Parabolic Reflector Design

We are seeking to produce a horizontally isotropic transmitter with a narrow vertical beam. Commercially available transmitters with sufficient power output do not have this property. Piezo film transmitters (eg from www.msiusa.com) with a cylindrical shape many wavelengths high can thoeretically produce such a beam pattern, however in practice the transmitter acoustic power is too low for a sonar ring application.

This paper considers the approach of designing a reflector to shape the beam of an existing transmitter. A parabolic reflector is shown in Figure 1 and this has the useful property that a point source located at the focus produces spherical wavefronts that are reflected into parallel plane wave fronts. In order to produce an isotropic horizontal beam, a cone with a parabolic cross section is proposed here.

Referring to Figure 1, the cone can be shaped from the section of the parabola above point V. Note that the point V is defined by the slope of the parabola being unity or 45 degrees. When the upper section of the parabola forms a axially symmetric solid with a rotational axis about the line FV, a right angled vertex is formed at V that is shaded in the figure. The distance between F and V is twice the focal length (ie 10 mm) where the focal length is the distance from F to the bottom of the parabola. A reflector with a diameter of 150 mm and a focal length of 5 mm has been machined using a CNC machine. The finished reflector is seen in Figure 2 with the vertex V now pointing upwards (ie 90 degrees rotated with respect to Figure 1). The reflector is machined from high density polystyrene. A smooth flat sample of this material was compared for absorption on reflection of ultrasound at 40 to 90 kHz and found to be equivalent to any smooth hard surface – that is a perfect reflector.

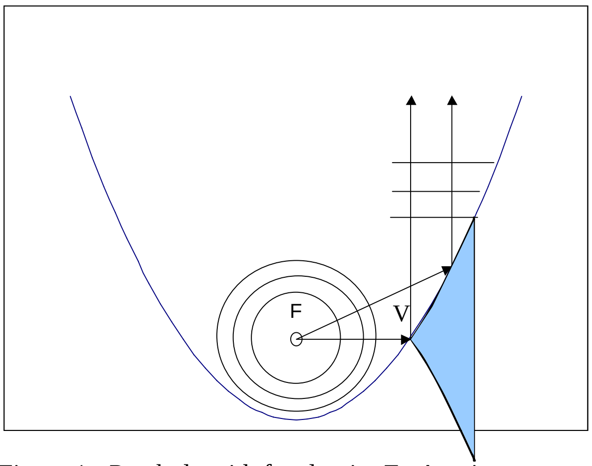


Figure 1 - Parabola with focal point F. A point source at F will result in circular wave fronts eminating from the focus F that when reflected by the parabola become plane wave fronts. The slope at V is 1. The shaded (blue) region is the cross section of the cone used as a reflector in this paper.

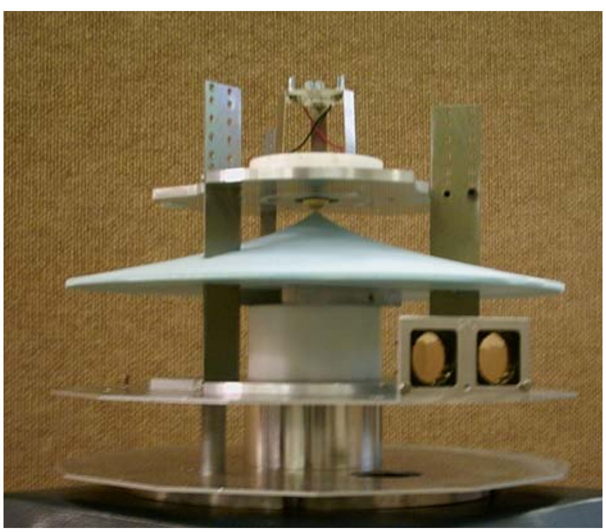


Figure 2 - The machined parabolic cone of diamter 300 mm mounted below the transmitter described later in the paper. Two Polaroid 7000 series transducers are shown below the reflector that will be part of the 48 receivers planned for the sonar ring.

3 TLM Simulation Study

Acoustic simulation is used to understand the properties of the reflector and the effects of the errors and variations in the position of the reflector with respect to the tweeter. Since it was not possible to accurately measure the effective acoustic centre of the transducer employed, an understanding of the effects of varying the position relative to the focal point of the reflector is useful information for designing and fine tuning the reflector.

Transmission Line Matrix modelling (TLM) was developed by Johns [Johns and Beurle 1971] and is a time domain, efficient method for modelling wave propagation. TLM has been employed widely in acoustic and electromagnetic applications [Flint, 2003, Kagawa et al, 1998, O'Connor and Cavanagh, 1997]. A 2D or 3D mesh is used to represent the propagating medium and time is also discretised. In each time increment waves travelling in each branch of the mesh in both directions are scattered at each node based on reflection and transmission properties of the branch impedances. The equations for scattering and connection are simple and easily implemented. The node spacing employed in this paper is 1/20 of a wavelength and this results in accurate modelling of the wave propagation and reflection at boundaries [Kagawa et al, 1998]. A 2D mesh representing up to 0.5 by 1 metres of air has been successfully simulated with C++ code written by the first author. Simulations take a few minutes to complete on a 2 GHz Pentium processor.

Since we are dealing with a cone reflector and the transducer is on the axis of the cone, the problem is axialsymmetric. Therefore the 3D problem can be reduced to a 2D problem since the pressure and particle velocity fields are the same for the same vertical dimension (*z* axis) and radius (*r* axis) from the axis of rotation. The vertical axis in the 2D representation shown in Figure 3 is the *z* axis and the horizontal axis represents the radius from the axis of rotation that is the left most vertical line. In axialsymmetric TLM, the propagating medium density of the 2D grid and characteristic impedance vary with *r* and this effectively models the changing spacing with radius between sectors in a 3D view of the discrete space [Kagawa et al 1998].

The simulation results shown in Figures 3 to 7 for two cycles of 45 kHz being transmitted at the commencement of the simulation from a point source located at the focal point of the parabolic conical reflector. We expect to see a plane wave emerging from the reflector propagating to the right. Note that there is interference between the direct and reflected wavefronts evident. Also the diffraction around the ends of the top plate and bottom reflector can be observed. The resulting far field propagation well clear of the reflector is not as clean as one may expect due to these effects.

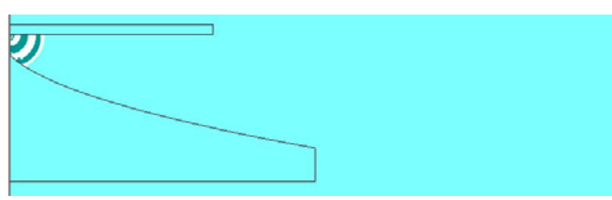


Figure 3 – The commencement of a TLM simulation of the conical reflector. The transmitter is modelled as a point source with a reflector immediately behind it near the top left of the simulation. Light areas are of high pressure and

dark represents low pressure.

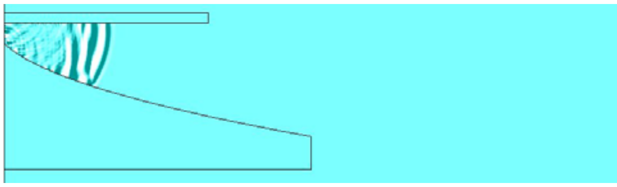


Figure 4 – Interference of direct and reflected wavefronts.

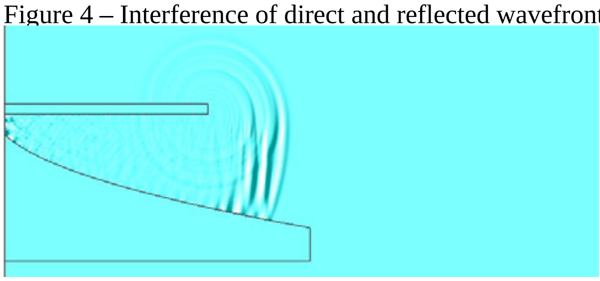


Figure 5 – Diffraction from the top plate evident.

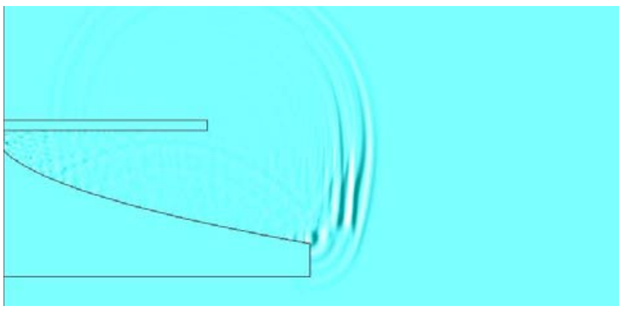


Figure 6 – Diffraction from the bottom reflector terminatin evident.

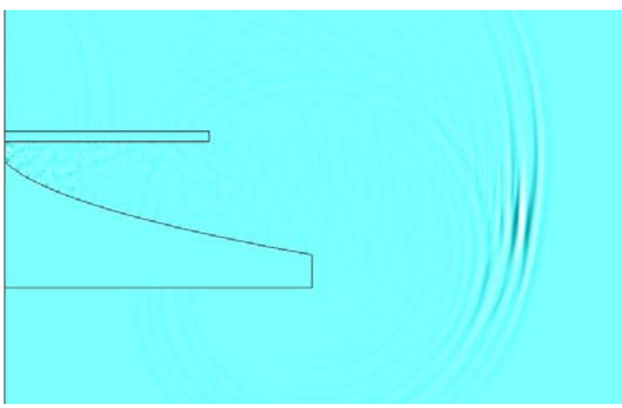


Figure 7 – Far field propagation.

Of interest is the effect of varying the spacing between the transmitter and the reflector, since the exact acoustic centre of a transmitter is difficult to determine in practice. In order to study this effect, 25 simulated microphones were placed a 1 metre to the right of the axis of axial symmetry spaced 0.5 degrees apart and spanning –6 degrees to +6 degrees. The reflector was displaced –7, -2, 0, 2 and +7 mm from the ideal focal position where negative is closer. The root mean squared (RMS) pulse amplitudes are plotted against the vertical angle of the microphone from the point on the axis half way between the bottom reflector edge and top plate in Figure 8. There are three effects evident: there is a shift in the maximum energy angle as the reflector is displaced; when the reflector is too close to the transmitter a loss in maximum energy occurs; and finally the beam width appears to be minimised for a displacement of –2 mm. This information is useful in fine tuning the real reflector position, and indeed the displacement was adjusted over a few millimetres to achieve a maximum response in the horizontal direction.

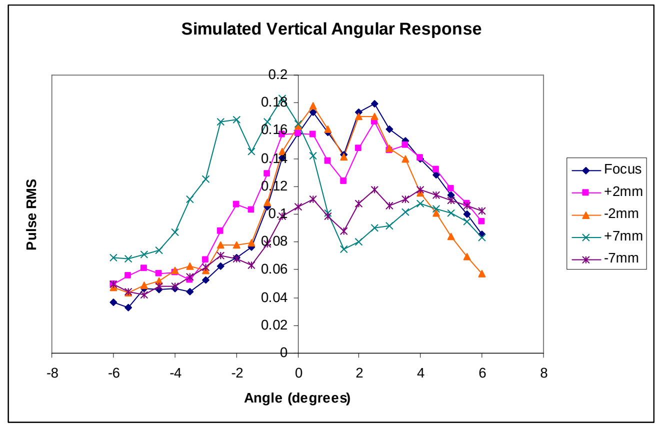


Figure 8 – RMS pulse amplitude versus vertical angle from the reflector at 1 metre for varying distance between the point source and the tip of the reflector.

4 Preliminary Tweeter Testing

Hi-Fi tweeters offer a high power handling capability but are usually limited in frequency reponse to the human audible range 10 to 20,000 Hz, thus limiting their applicability to sonar applications. However some manufacturers claim that extending the frequency response of a loadspeaker beyond 20 kHz can make a decernible difference to human perception. Whether this is correct is immaterial as far as this paper is concerned. What is interesting is that commercial tweeters are available that specify a frequency response extending to 100 kHz at power levels of interest to the sonar researcher. Murata offer the ESTD01 "Super Tweeter Driver" [Murata 2006] as shown in Figure 9 with frequency range 15 to 100 kHz at 90dB/W/m that offers the unique characteristic of a hemispherical "breathing" vibration mode as illustrated in Figure 10. This approximates a point acoustic source with a wide beamwidth of 60 degrees at -10 dB with 1 W white noise [Murata 2006].

The ESDT01 tweeter was tested with its housing and grille attached as shown in Figure 9 with an excitation pulse of 3 cycles at 60 kHz. The sound emitted was measured on axis with a Bruel Kjaer Cartridge type 4135 ¼" condenser microphone with a flat frequency response certified to +- 2dB up to 100 kHz. The microphone calibration is 3.39 mV rms per Pa RMS (unit gain) and on +20 dB gain setting during the experiments, 100 dB = 68 mV rms.

The resulting received pulse contained many pulses due to reverberation within the grille and housing. The transducer was removed from its housing and grille and most of the reverberation pulses disappeared. The frequency response was measured within +- 6 dB up to 80 kHz above which the response dropped off markedly. The transducer was tested with its off axis response using 2 cycles at 45 kHz and the results are shown in Figure 11. Note that the pulse shape is not exactly the same for equal angles either side of the axis – that is the transducer is not perfectly symmetrical. Note also the presence of some limited reverberation in the response.

The ESTD01 tweeter angular response is summarised in Figure 12 where the Sound Pressure Level in dB is shown.

Figure 9 - ESDT01 transducer front and rear view with housing and grille – picture from [Murata 2006].

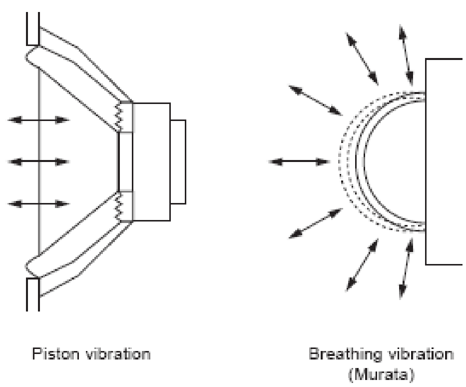
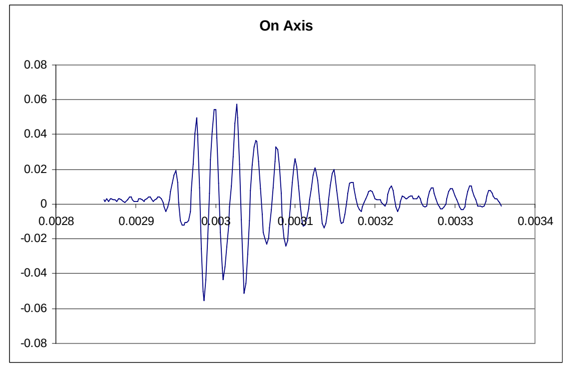
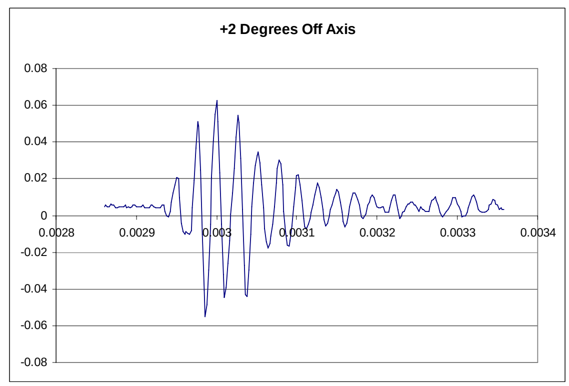
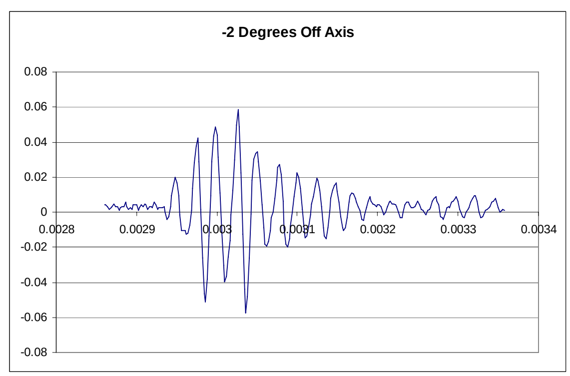
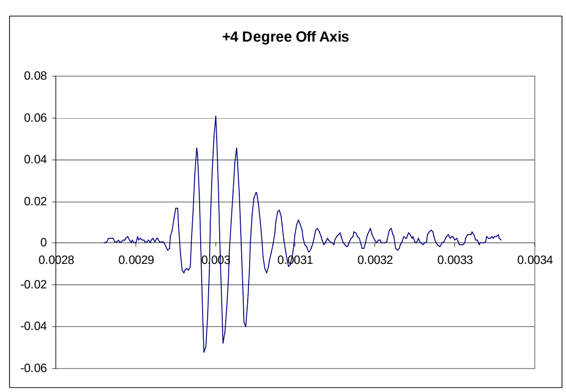


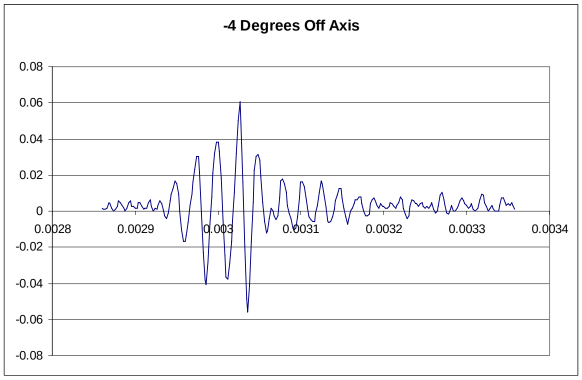
Figure 10 - Cross sectional comparison of vibration of a piston versus the ESTD “breathing” vibration – taken from [Murata 2006] .

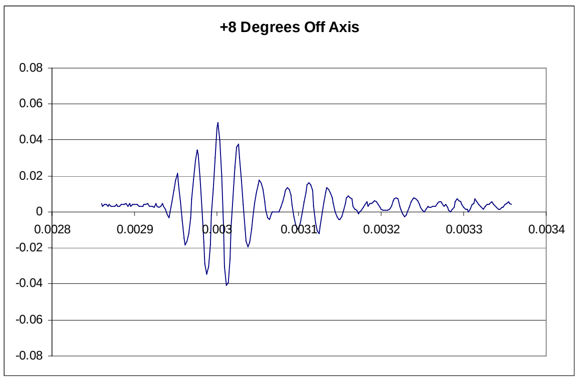












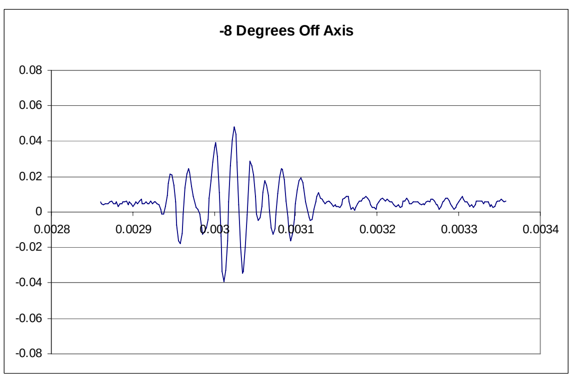


Figure 11 - Off axis free air response of the ESTD01 transducer with its housing removed. Measurements taken with Bruel Kjaer Cartridge type 4135 ¼" condenser microphone with the ESTD01 driven with 2 cycles of 45 kHz at 65 Volts peak to peak. The time axes are in seconds and the vertical axis is in Volts. All measurements were taken at 1 metre with the microphone on +20dB setting.

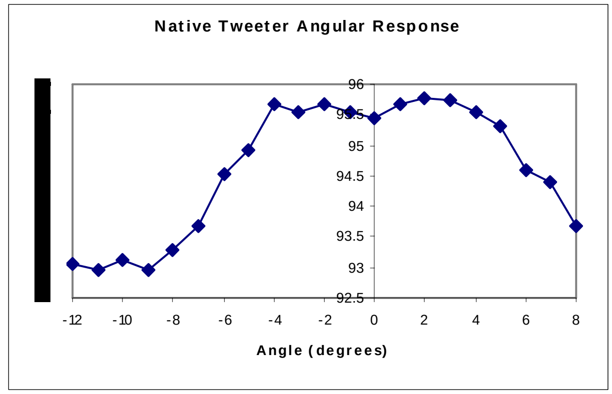


Figure 12 Measured Tweeter Response to 2 Cycles 65 Volts 45 kHz peak to peak versus angle from axis.

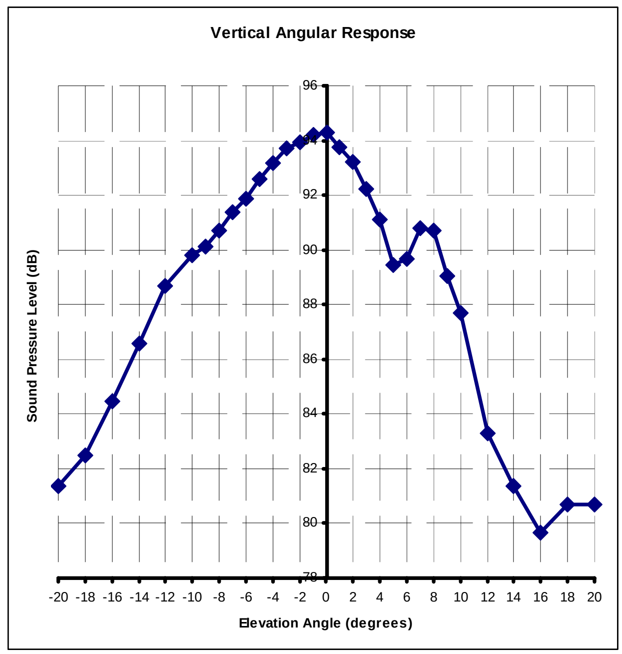


Figure 13 - Measured sound pressure level dB for differing elevation angles for the parabolic cone – transducer combination. Positive angle is above the transmitter. Two cycles of 45 kHz is emitted from the ESTD Murata tweeter and the measured sound pressure level is reported.

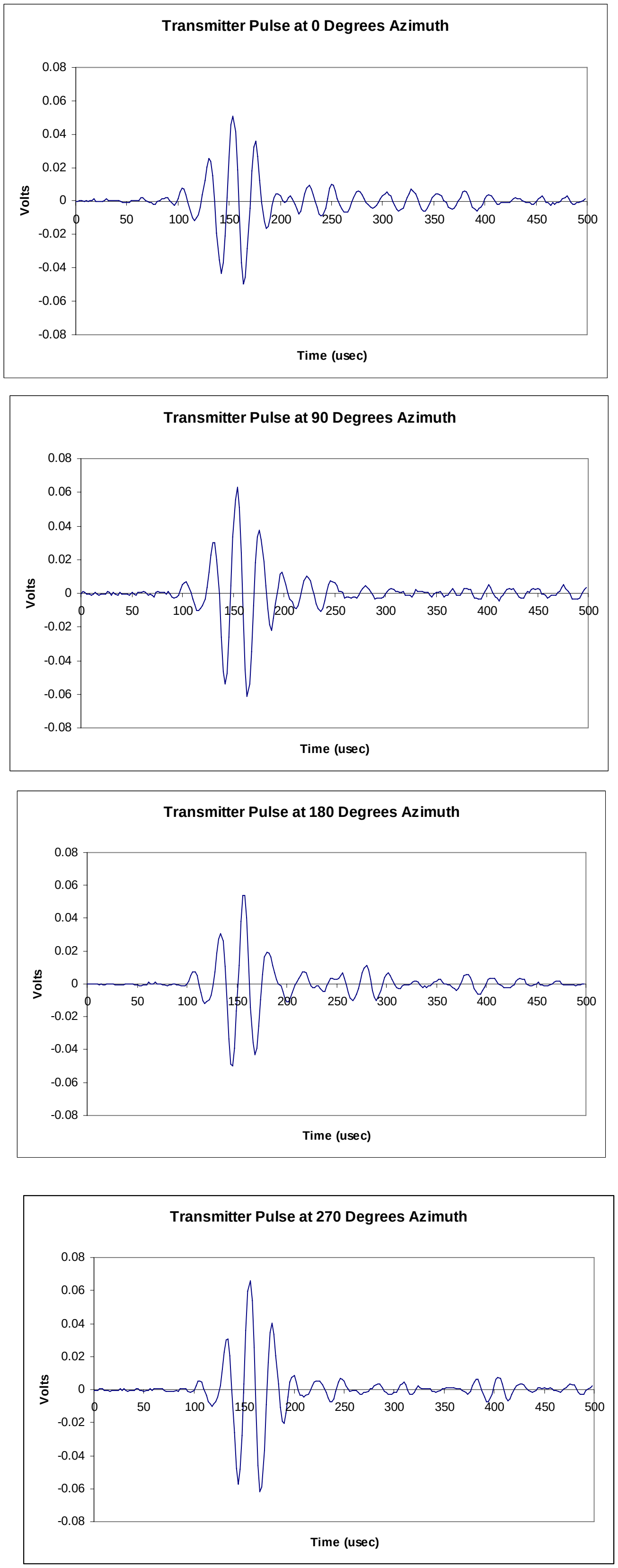


Figure 14 – Final Design of reflector and transmitter pulse shapes at different angles around the sonar ring.

5 Reflector Design Characterisation

The testing of the combination of the reflector and the ESTD01 tweeter is discussed in this section. Firstly the height of the tweeter above the reflector was adjusted to give the maximum response to 2 cycles at 45 kHz in the horizontal plane – a procedure motivated by the simulation results. The frequency of 45 kHz was chosen to give the best response for the combination of the tweeter and the series 7000 Polaroid transducer that will be employed as a receiver in the final sonar ring design.

The vertical beam response of the reflector design was tested with varying elevation angles and measurements taken using the Bruel Kjaer ¼" condenser microphone in response to a 65V 2 cycle 45 kHz signal to the ESDT01 tweeter from a power amplifier fed from a signal generator. The sound pressure level versus elevation angle is shown in Figure 13. The –3dB angles are approximately +- 8 degrees. The local minimum in the graph at +5 degrees is due to interference between two overlapping pulses that develop off axis.

The uniformity of pulses emitted from the sonar ring as the azimuth angle varies are shown in Figure 14 for each 90 degrees and all measurements taken in the horizontal plane. Other angles are similar in shape and amplitude. The effect of the 1 mm wide supporting bars slightly obscurring the outgoing pulses is negligible due to the wavelength (~6 mm) being much wider than the bars. The variability between different azimuth angles is most likely due to the asymmetry in the tweeter seen in Figure 11. In fact it is quite remarkable that such clean pulses are obtained in light of the earlier results!

6 Intensity Comparison

The pulse amplitude at 1 metre was compared to the DSP sonar unit previously reported [Kleeman 2004] that is capable of ranging to well over 4 metres. The DSP sonar produced a pulse at 1 metre of 107 dB SPL directly in front of the transmitter compared to the sonar reflector configuration in this paper of 94 dB – a difference of 13 dB. This difference is ameliated by the following points: In the advanced sonar ring [Fazli 2006], the amplitude of the transmitter pulse is reduced by an off axis angle of 7.5 degrees which results in a 101 dB or just 7 dB above the SPL in this paper. Moreover the noise on a transceiver channel in the analogue electronics (as opposed to a dedicated receiver channel) is approximately 4 times higher (= 12 dB). It is therefore anticipated that the performance of the reflector transmitter in this paper may be superior in signal to noise mid way between discrete transmitters' centres.

7 Conclusions and Future Work

The paper has presented a new design for a single transmitter for a sonar ring based on a parabolic conical reflector. The new design produces a reasonably uniform emitted pulse amplitude around the ring compared to that produced by many discrete outward facing transmitters in designs employed previously. The vertical beamwidth of the reflector design is restricted to approximately 16 degrees within the –3dB points. The design has been simulated and tested experimentally.

Naturally the next step in the design of a sonar ring is to incorporated the receivers and the signal processing. The existing hardware associated with the DSP sonar ring reported in [Fazli and Kleeman 2006] could be deployed with the new transmitter design. Another alternative that is underway is the design of a FPGA hardware parallel processing solution for all 48 receiver channels using on-the-fly matched filtering. A feasibility study has shown that this is possible on a Xilinx Virtex 2 device. Another project underway is the use of CTFM in conjunction with a FPGA to exploit the transmitter structure of this paper.

Acknowledgements

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