EXPERIMENTAL COMPARISON OF MEASURED ULTRASOUND PRESSURE FIELDS WITH THEORETICAL PREDICTION

John P. Powers; LT Benito Baylosis, USN; LTjg Peter Gatchell, USN; and LT William Reid, USN
Department of Electrical and Computer Engineering (Code EC/Po)
Naval Postgraduate School
833 Dyer Road, Room 437
Monterey, CA 93943-5121 USA

INTRODUCTION

We have presented a technique in the past [1–3] to calculate the acoustic potential and pressure from knowledge of the excitation spatial and temporal velocity function. In this paper we wish to present a comparison of a predicted field from using the technique with experimentally measured data.

REVIEW OF PROPAGATION SIMULATION TECHNIQUE

Our propagation simulation uses fast Fourier spatial transforms to rapidly calculate the spatial impulse response wave, $h(x, y, z, t)$, at a location z in front of the source. The complete temporal response can be found by convolving the impulse response $h(x, y, z, t)$ with the time excitation waveform $T(t)$.

Figure 1 shows the geometry of the problem. The source is assumed to be located in a planar rigidly baffled region shown at the bottom of the figure. The normal velocity of the source is assumed to be known and separable ($v(x_0, y_0, 0, t) = s(x, y)T(t)$); we want to find the excited wave at the observation point (x, y, z) (or in the entire parallel plane located a distance z away from the source plane) as a function of time. The medium is assumed to be linear, lossless, and homogeneous and has a velocity of 1500 m/s (i.e., water). Based on these assumptions, the propagation simulation technique [1,2,3] follows linear systems theory.

The acoustic potential $\phi(x, y, z, t)$ is found [1,2,3] from

$$\phi(x, y, z, t) = T(t) \mathop{*}_{t} \mathcal{F}^{-1} \{\tilde{s}(f_x, f_y)\tilde{g}(f_x, f_y, z, t)\} , \qquad (1)$$

where $T(t)$ is the known time dependence of the source (see Fig. 2), $\mathcal{F}_{xy}^{-1}$ is the two-dimensional inverse spatial Fourier transform operator, $\tilde{s}(f_x, f_y)$ is the two-dimensional spatial Fourier transform of the spatial portion of the separable excitation function, and $\tilde{g}(f_x, f_y, z, t)$ is the two-dimensional spatial Fourier transform of the Green's function. This transform of the Green's function is usually solvable for simple aperture

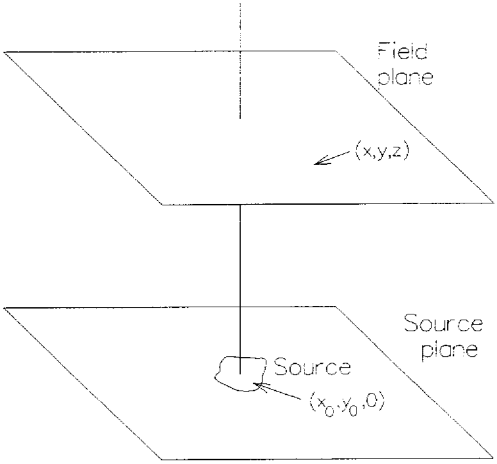


Figure 1: Geometry of source and receiving plane.

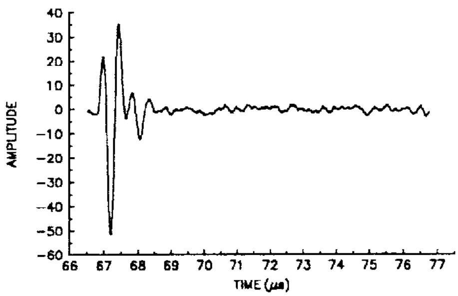


Figure 2: Measured temporal response of source, using wideband PVDF transducer.

geometries. For the rigid baffle and propagation into the half-space of lossless media, this transfer function is known [2] to be

$$\tilde{g}(f_x, f_y, z, t) \quad = \quad J_0\left(\rho\sqrt{c^2t^2 - z^2}\right) H(ct - z) \qquad (2)$$

2π

where $\rho = \sqrt{f_x^2 + f_y^2}$ and $H(\cdot)$ is the Heaviside step function.

The method for simulating propagation, then, is

1. Find the two-dimensional Fourier transform of the assumed $s(x, y)$.

2. For each desired value of z and t, multiply the result with $\tilde{g}(f_x, f_y, z, t)$ (Eq. 2).

3. Take the inverse two-dimensional inverse transform of the product to find the spatial impulse response, $h(x, y, z, t)$.

4. If desired, find the output for various $T(t)$ by convolving $T(t)$ with $h(x, y, z, t)$.

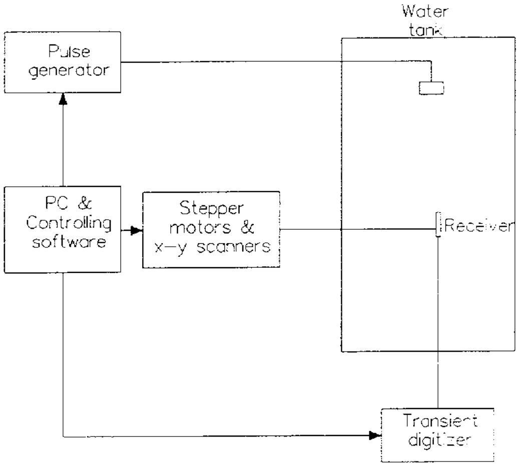


Figure 3: Block diagram of experimental measurement system.

5. If desired, find the wave pressure $p(x, y, x, t)$ from

$$p(x, y, z, t) = \rho_0 \frac{\partial \phi}{\partial t}, \tag{3}$$

where ρ_0 is the density of the medium.

This simulation technique has been implemented in Fortran [4] and in MATLAB [5,6]. The following studies were produced with the MATLAB models.

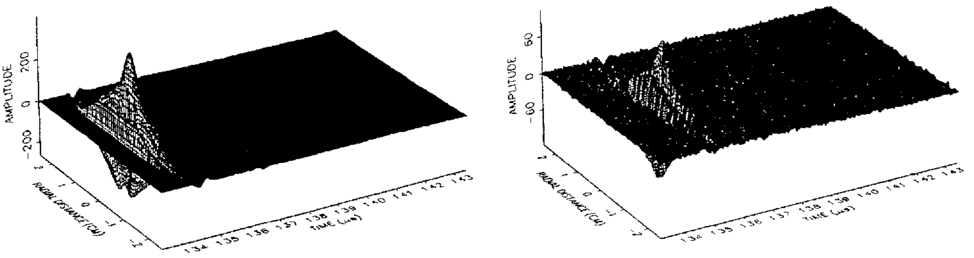
EXPERIMENTAL MEASUREMENTS

Figure 3 shows a block diagram of the experimental system [7] that was used to measure the time-varying acoustic field. The measurement was under the control of a computer running a LabView program that controlled all aspects of the measurement. This setup scanned a piezoelectric point receiver (or, alternatively, a PVDF receiver) in an x-y raster pattern. The pattern was generated by stepper motors under the control of the LabView software. At each measurement position, the software triggered the pulsed source and recorded the digitized received signal.

The source was a circular piston transducer that was 1.27 cm in diameter. The sample area was 5.12 cm x 5.12 cm (31 samples). There were 128 x 128 samples taken (at a sample spacing of 0.4 mm). (In the figures, only a limited portion of the sample space is shown, samples 33 through 96.) There were 436 samples in the time domain for each spatial sample location.

RESULTS

Figure 4 show perspective views of these spatial excitation functions for a circular source with a diameter of 31 samples at a distance of 0.2 m from the source [9]. Due to the four-dimensional nature of the recorded waveform (amplitude, two lateral spatial dimensions, and time), only a slice of the recorded waveform $h(r, 0, t)$ is shown. There are 128 samples in the lateral dimension and 106 samples along the time axis. The



(a) Predicted. (b) Measured.

Figure 4: Comparison of (a) predicted and (b) measured amplitude values for a propagation distance of 0.2 m.

plotted time interval begins just before $t = z/c$, i.e., just before the first arrival of the first part of the wave at the observation plane.

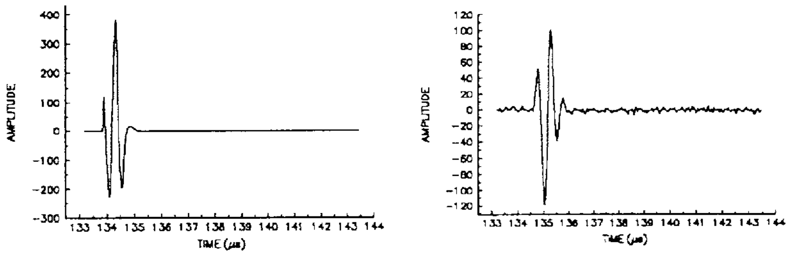
Figures 5 and 6 show the predicted and measured time response curves at $r = 0$ and $r = 0.65$ cm lines, respectively, for the same 0.2 m distance from the source [9]. Again, the plotted time interval begins just before $t = z/c$.

We observe from Figure 4 that the waves are qualitatively very similar. The pressure wave shows a positive rise followed by a negative portion, returning gain to a positive value. Figure 5 shows a more quantitative view. (This view is a time history taken through the $r = 0$ sample point.) It shows general agreement in the shape of the waves. The predicted first downward spike is not as deep as the measured downward spike. Similarly, the measured positive spike is not as high as predicted. Similar behavior is seen in Fig. 6 which shows the predicted and measured time-varying behavior taken at the $x = 0.635cm, y = 0cm$ sample location. The general shape of the predicted waveform appears correct, but the values of the peaks of the waves do not match exactly.

The source of the errors is felt to lie predominantly in the alignment of the sample plane with the source plane. As shown in Fig. 1, the predictive model requires that the source and sample plan be parallel; this is difficult to achieve in practice. One possible solution would be to more carefully align the planes using a cw source and the resulting phase measurement to perform an interferometric alignment.

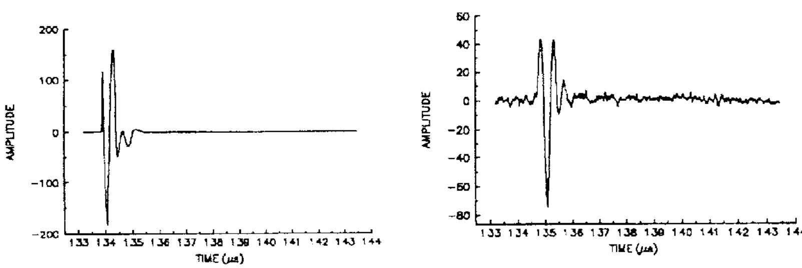
SUMMARY

This paper reported a comparison of experimentally measured ultrasound pressure fields from a test transducer with predictions from an acoustic diffraction model. The diffraction model uses a computationally efficient technique combining two-dimensional spatial Fourier transforms with temporal convolution to predict the acoustic potential and pressure fields from a pulsed source with an arbitrary spatial excitation function.



(a) Predicted. (b) Measured.

Figure 5: Comparison of (a) predicted and (b) measured values of time response along the $r = 0$ line.



(a) Predicted. (b) Measured.

Figure 6: Comparison of (a) predicted and (b) measured values of time response along the $r = 0.635$ cm line.

The propagation model has been implemented in the MATLAB programming environment and run on PCs and UNIX workstations. A pulsed ultrasound data collection facility that scanned a point receiver in a plane located an arbitrary distance from a circular source collected the experimental data. The collection process is automated and controlled by a LabView program. The source was excited as a piston with a single cycle tone burst and the measured data was digitized and recorded under the control program. The predicted pressure fields and the measured pressure fields were displayed in a three-dimensional graphical format for comparison. Qualitative comparison of the measured and predicted fields appear to be in good agreement.

ACKNOWLEDGEMENTS

This work was sponsored by the Direct-Funded Research Program of the Naval Postgraduate School with the cooperation of the Office of Naval Research. The Space and Naval Warfare Command also provided partial support.

REFERENCES

[1] D. Guyomar and J. Powers, "Propagation of transient acoustic waves in lossy and lossless media," *Acoustical Imaging, Vol. 14,* A.J. Berkhout, J. Ridder, and L.F. van der Wal, Eds., Plenum Press: New York, pp. 521–531, 1985

[2] D. Guyomar and J. Powers, "A Fourier approach to diffraction of pulsed ultrasonic waves in lossless media," *J. Acoustical Society of America*, vol. 82, no. 1, pp. 354–359, 1987.

[3] D. Guyomar and J. P. Powers, "Boundary effects on transient radiation fields from vibrating surfaces," *J. Acoustical Society of America*, vol. 77, no. 3, pp. 907–915, 1985.

[4] T. Merrill, *A transfer function approach to scalar wave propagation in lossy and lossless media*, Master's thesis, Naval Postgraduate School, Monterey, California, March 1987.

[5] W. R. Reid, *Microcomputer simulation of a Fourier approach to ultrasonic wave propagation*, Master's thesis, Naval Postgraduate School, Monterey, California, December 1992.

[6] J. P. Powers, "Acoustic propagation modeling using MATLAB," Tech. Rep. NPS EC–93–104, Naval Postgraduate School, Monterey, California, September 1993.

[7] P. A. Gatchell, *Experimental hardware development for a pulsed ultrasonic data collection facility*, Master's thesis, Naval Postgraduate School, Monterey, California, June 1994.

[8] B. E. Baylosis, *Acoustic imaging of ultrasonic wave propagation*, Master's thesis, Naval Postgraduate School, Monterey, California, December 1994.