LOCALIZED WAVE TRANSPORT OF PULSED BEAM ENERGY

D. Kent Lewis, Richard W. Ziolkowski, Bill D. Cook #

Lawrence Livermore National Laboratory,
Livermore, CA 94550, U.S.A.

University of Houston, TX 77004, U.S.A.

INTRODUCTION

This paper describes the theory and experiments used to measure a new type of finite beam pulse, the localized wave pulse. The LW pulse is a linear superposition of Gaussian-like basis functions which are constructed from the focus wave modes of Brittingham [1] by means of the modified power spectrum [2].

Experiments to date have made use of three techniques. Synthetic array experiments using acousto-optic measurements were first undertaken to see if the localized wave pulses could be launched by normal acoustic devices. Next, synthetic array two transducer measurements were done to see if the beam generated would outperform a conventional continuous wave or pulsed array with both Gaussian shading and no shading. Finally, real array experiments were performed to see if the beam could be launched with actual acoustic arrays and still perform as well as in the synthetic array measurements.

In all cases, the LW pulse has outperformed comparable beams by a wide margin. The theory will be outlined and the methods of measurement sketched. Finally, comparison of beams produced by driving the array with different inputs will be presented.

THEORY

The basis functions of the LWT signals propagating along the z axis are the focus wave modes;

$$\Phi_k(r, t) = e^{ik(z+\alpha)} \frac{e^{-kp^2/(z_0+i\zeta)}}{4\pi(z_0+i\zeta)} \quad \text{equ. 1}$$

with z_0 a constant, k the wave number, z the axial distance, c the wave speed, t the time, and $\zeta = z - ct$. The wave field at any position and time t can then be defined as

$$f(r, t) = \int_0^\infty \Phi_k(r, t) F(k) dk \quad \text{equ. 2}$$

The trick is to find a spectrum, $F(k)$ for which $f(r, t)$ is highly

localized in the region desired. Using the focus wave basis function, the field becomes

$$f(r, t) = \frac{1}{4\pi[z_0 + i(z - ct)]} \int_0^\infty F(k) e^{-ks(p, z, t)} dk \quad \text{equ. 3}$$

where

$$s(p, z, c) = \frac{p^2}{z_0 + i(z - ct)} - i(z + ct) \quad \text{equ. 4}$$

The requirements on the spectrum, $F(k)$, are that it lead to a finite energy in the wave field and that it introduce other parameters in order to allow the field to be tweaked for maximum localization in the region desired. The spectrum used is obtained from

$$F(k) = k^{\alpha-1} e^{-ka} \quad \text{equ. 5}$$

by a scaling and truncation and is called the Modified Power Spectrum (MPS), defined as

$$F(k) = 4\pi i \beta \frac{(\beta k - b)^{\alpha-1} e^{-a(\beta k - b)}}{\Gamma(\alpha)} \begin{cases} \left(k > \frac{b}{\beta}\right) \\ = 0 & \left(0 \leq k \leq \frac{b}{\beta}\right) \end{cases} \quad \text{equ. 6}$$

This choice fulfills the finite energy requirement and introduces the four new parameters, a , α , b and β , in addition to z_0 contained in the focus wave mode expression. This yields a wave function on axis as

$$f(p=0, z=ct) = \left[\frac{\cos(2bz/\beta) - (2z/\beta a) \sin(2bz/\beta)}{1 + (2z/\beta a)^2} \right] \frac{1}{az_0} \quad \text{equ. 7a}$$

which behaves in the different regions along z as

$$= \frac{1}{az_0} \quad \left(\frac{2bz}{\beta} \ll 1 \text{ and } \frac{2z}{a\beta} < 1 \right) \quad \text{equ. 7b}$$

$$= \frac{\cos(2bz/\beta)}{az_0} \quad \left(\frac{2z}{a\beta} < 1 \right) \quad \text{equ. 7c}$$

and

$$= - \left[\frac{\sin(2bz/\beta)}{(2z_0/\beta)} \right] \frac{1}{z} \quad \left(\frac{2z}{a\beta} > 1 \right) \quad \text{equ. 7d}$$

the three regions of different behavior for the wave function. Thus the amplitude on axis is constant for a distance, then begins to oscillate recovering its original amplitude every $\pi\beta/2b$, then while still oscillating falls off as $1/r$ as it must to obey the radiation condition.

EXPERIMENTAL PROCEEDURE

Three experimental efforts have been completed to date. The first of these was a measurement of the field using an acousto-optical measurement system and synthetic array methods to determine the pressure over an area 20.48 microseconds long and 6 cm wide. A single transducer, a 5 MHz 3 mm radius commercial unit, was used to launch each of 11 waveforms, L_0 through L_{10} , at 21 different positions 3 mm apart. The waveforms were computed and loaded into an arbitrary waveform generator, then recalled by name. A schematic of the experimental arrangement is shown in figure 1.

Since acousto-optical detection is over a line, reciprocity was used to interchange the role of transmitter and receiver. The theoretical model used for comparison consisted of a 21 by 21 element array with inter-element spacing of 3 mm. All of the elements in a row along x fire the same signal and each row fires a different signal in an arrangement along y symmetric about the center of the array. The excellent results of this first test of the theory, a measurement of the field along y and time or z, led us to the second set of experiments.

The second method was also a synthetic array model. The same transducer was used to generate the fields and a second transducer with similar properties replaced the laser and photo-diode. The receiving transducer was positioned at 441 different positions in x and y, separated again by 3 mm, and at each position the 11 LW waveforms were launched as well as continuous wave (CW) tone bursts of 0.5, 1.0 and 2.0 MHz. The tonebursts were 8 microseconds in duration. For field comparison purposes, the center portion of each CW field was extracted and processed to avoid the turn-on and turn-off effects from the power amplifiers.

The third series of experiments used a 25 element, highly damped PVDF acoustic array with a nominal resonant frequency of 5 MHz. The elements were arranged in a 5 by 5 pattern and were individually addressable. The element diameter is 0.5 mm and the elements are separated by a 2.5 mm center to center distance, making this a sparse array.

The signals were modified from the two previous experiments by a folding process, a method of mapping the driving functions of a larger array into the actual array. These signals were then further modified by a time gate which removed part of the resultant signals for efficiency. These were then used as the input signals to the array.

The experimental system was modified by using two waveform generators and a demultiplexer unit which separated the signal from one of the generators into 5 different signals for the array elements. The signals were fed to the array symmetrically about the center so 6 waveforms were needed. The resultant sample interval for the source signals was still well within acceptable frequency limits for all waveforms.

The detection in the third series of experiments was again by the same transducer used for the previous experiments. The measurements were of pressure as a function of time in 0.5 mm steps along x at y=0 and along

FIGURE 1. The experimental system schematic. The synchronization signal controls both the launching of the individual waveforms and, after a delay to compensate for propagation, for detection of the pressure field. In the acousto-optic experiments, a lens is used to project a virtual image of the photo-diode close to the sound beam.

y at x=0 for -5 to +5 cm relative to the center of the array. For comparison purposes a 0.5 MHz piston beam was also launched.

DATA PROCESSING AND RESULTS

The first series of experiments was undertaken to see if the fields predicted by theory could really be created, so an analysis of this data involved only the comparison of measurement to prediction. Since this agreement was excellent, the two transducer experiments were begun immediately.

For the two transducer synthetic array, the tone bursts were assembled in the signal processing package VIEW. The resultant fields were assembled as both piston or uniform amplitude and Gaussian beams by proper weighting of the 6174 individual waveforms at each z value for comparison. The half width at half maximum for the CW cases and the LW beam are shown in figure 2.

As expected, the Gaussian beams for all frequencies were much wider than either the LW or the piston CW beams for all cases. An indication of the complicated near field structure of the CW signals can be seen in the half widths for the higher signals.

Additionally, beams made up of the center driving function L_0 were formed as both Gaussian and piston simulations. This signal has a spectrum that is the envelope of all the frequencies in the LW signals. This comparison was done to see if the broadband signals alone could account for the localization of the beam. We also Fourier analyzed the fields as magnitude versus frequency and beam position to look for frequency shedding, the progressive loss of low frequency content in the pulse.

For comparison purposes, we determined the equivalent frequency in the following way. All of the input signals were Fourier transformed, their magnitudes multiplied by the number of elements each fired, and the results summed. This magnitude was then integrated and the e^{-2} point chosen for comparison. This point was well below 0.5 MHz.

FIGURE 2. Beam width for 441 element simulated array. The CW signals are obtained by driving all elements with the same amplitude. The simulated array is 6 cm. by 6 cm.

The on axis intensities and energies are in all cases higher for the LW pulse than for any of the others. Some frequency shedding was observed in the L_0 pulse in that the upper half power point remained fairly constant while the lower increased with increased distance traveled. The LW pulse did not exhibit this low frequency shedding leading us to a description of the pulse as a moving interference pattern. Apparently enough of just the right frequencies arrive on axis from the various sources at just the right time to reconstruct the pulse.

The third series of measurements using the 25 element array used only 6 signals. While not an ideal situation, the experiment allowed us to see if inter-element array effects would preclude actual launching of the pulse.

Figure 3 shows the on axis energy for the LW pulse compared to a 1/2 MHz CW toneburst. Both signals were launched from the array and detected by the transducer used before. The energy is determined for both cases by integrating the intensity of the on axis signal over the time of the pulse for the LW signal and over the chosen window for the toneburst. The normalization is calculated by determining the total energy generated in the water by an equivalent set of point sources.

The results for this case showed that the LW can indeed be generated by a real array. Further, these results show that the resultant beam, though generated by only 6 signals and 25 elements, will still beat a comparable CW beam by a factor of 4 in energy on axis.

FIGURE 3. The energy of the LW beam on axis compared to the energy of the 1/2 MHz CW toneburst. The normalization energy is a calculation of the total energy put into the water by the array elements assuming they are point sources. The experimental energy is obtained by integrating the intensity over time.

SUMMARY

We have addressed three questions in this research: 1) can the LW signals be generated by real acoustic devices; 2) will these signals interfere with each other in the presense of noise and minor misalignment well enough to form a pulse which will behave as predicted; 3) can these signals be generated simultaneously by an actual array, or will the inter-element interactions make the launching of an actual pulse impossible. The results to date have been overwhelmingly positive and indicate that this is a real, as opposed to a mathematical, effect.

Our research plan is currently focusing on three main areas: 1) propagation of the LW pulse through mode-converting interfaces and in dispersive media; 2) generation of the LW pulse using broad bandwidth, high power-high efficiency transducer arrays; 3) resolution determination in imaging experiments.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Dale W. Fitting of N.I.S.T., Boulder, Colorado for the array used in the third series of experiments. Thanks also to Ken Waltjen and Denis Silva for the demultiplexer units. Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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