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Acousto-optical confirmation of the localized wave phenomena

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ABSTRACT

An acousto-optical measurement method is described which was used to conduct proof of principle experiments for a novel acoustic pulse system. The pulse theory, the Localized Wave pulse, is discussed and the system explained and described. The results of the experiments confirm the Localized Wave theory.

2. INTRODUCTION

In 1983, Brittingham¹ developed a transverse solution to Maxwell's equation which he called Focus Wave Modes (FWM). This family of solutions has the property of being highly localized in both space and time. The solutions maintain their energy distribution for all time and travel at the wave speed in any linear medium. They also require an infinite amount of energy to produce and can only be projected through an infinite aperture. They are, therefore, physically impossible in exactly the same way that infinite plane waves are impossible.

Ziolkowski² realized that since these wave solutions were equivalent to infinite plane waves, they could be used as basis functions to create new, finite energy solutions which obeyed the radiation conditions. He formed the Modified Pulse Spectrum (MPS) from a simple spectrum by scaling and truncation and showed that the pulses formed in this way maintained their localization better than any other known pulse.

Much theoretical work has been done to develop the practicality of this idea in the electromagnetic area. However the source signals must be individually shaped for each array element, and the digital to analog converter equipment needed for microwave experiments is simply not available at present due to the GHz frequencies needed. The localized wave effect is a wave phenomenon however, so proof of principle experiments could be carried out in the acoustic environment.

The frequencies for the acoustic case scaled to less than one MHz, and the array size could be set at 6 cm for a reasonable experiment. Equipment was available to generate any arbitrary waveform that could then be fed to an ultrasonic transducer. A positioning system was available to position the sending transducer precisely.

An analysis of transducer disk to transducer disk coupling^{3,4} showed that any measurement would be the third time derivative of the source signal to the array element plus a distortion which depends on the disk sizes and their separation. The disk to line coupling⁵, which is a model of our acousto - optical detection system, gives the same derivatives but with little distortion. Since we wished to prove that the necessary signals could be launched, we decided to use this technique.

3. THEORY

3.1 Focus Wave Modes

The FWMs are related to solutions that represent Gaussian beams propagating with only local deformation, i.e., a Gaussian-shaped packet that propagates with changes only within the packet. Such a pulse, moving along the z axis, with transverse distance denoted by ρ

$$\Phi_k(\mathbf{r}, t) = \left\{ \frac{e^{-k\rho^2/[z_0 + i(z - ct)]}}{4\pi i[z_0 + i(z - ct)]} \right\} e^{ik(z + ct)}$$

is an exact solution of the scalar wave equation. This equation describes the fundamental solution which is a Gaussian profile beam that translates through space-time with only local variations.

These fundamental pulses appear as either a transverse plane wave or a particle, depending on whether k is small or large. For all k they share with plane waves the property of having finite energy density but infinite total energy.

Ziolkowski recognized that a superposition of the FWM pulses can produce finite-energy solutions to the wave equation and to Maxwell's equations^{2, 6}. The variable k in the solution provides an added degree of freedom, and these fundamental Gaussian pulse fields can be used as basis functions, a superposition of which could represent new transient solutions of the wave equation. In other words, these infinite-energy solutions can be added together, with the proper weighting, to yield physically realizable, finite-energy solutions.

For example, either the real or imaginary part of the function

$$f(r,t) = \int_0^\infty \Phi_k(r,t) F(k) dk$$

is also an exact, source-free solution of the wave equation. The $F(k)$ function is the weighting function (the spectrum), and the resulting pulses have finite energy if $F(k)$ satisfies certain integrability conditions⁵. This representation uses basis functions that are localized in space and are therefore a natural basis for synthesizing pulse solutions that can be tailored to give directed wave energy transfer in space. A bi-directional representation is also possible, which leads to analogous solutions in geometries that have boundaries (propagation of waves in waveguides).

Ziolkowski considered several different solutions to the wave equation and Maxwell's equations. A particularly interesting spectrum he investigated was a modified power spectrum (MPS), which yields the associated MPS pulse

$$f(r,t) = \text{Re} \left[\frac{1}{z_0 + i(z - ct)} \frac{1}{\left(\frac{s}{\beta} + a \right)^\alpha} e^{-bs/\beta} \right]$$

where α and β are parameters that we adjust to achieve specific characteristics, and s is defined by

$$s = \frac{\rho^2}{z_0 + i(z - ct)} - i(z + ct)$$

This pulse can be optimized so that it is localized and its original amplitude is recovered out to extremely large distances from its initial location. In particular, for a distance $z \ll \beta/2b$ and $z < \beta a/2$, the amplitude of the pulse at the pulse center is constant. It then becomes oscillatory with an oscillation length of $\pi\beta/b$ in an intermediate zone, $\beta/2b < z < \beta a/2$, recovering its original amplitude when $z = n(\pi\beta/b)$, n being any positive integer. Finally, when the observation point is very far away from the origin, $z > \beta a/2$, the MPS pulse decays like $z^{(-\alpha)}$.

3.2 Acousto - Optical Detector

The measurement system chosen differentiates the fields in the following way. The transducer differentiated the input waveform one time³, corresponding to the forward propagating pulses from the front and back faces. Some care is needed in matching the pulse width to the transducer's resonant frequency to avoid excessive overlap of the two pulses which, for a disk that is too thin, would reduce the signal. Similarly, a disk which is too thick would lead to a separation of the pulses, and make the radiated pulse different than a simple derivative.

The acoustic beam creates a phase grating in the water for a single acoustic frequency. For a pulse, the frequencies superpose and the resulting pressure pulse behaves as a change in refractive index which propagates at the speed of sound.

The laser is oriented at a right angle to the acoustic beam. We can look at this interaction of the light and sound as if a complicated lens passes between the laser source and the photo - diode. The resulting change in the originally parallel light rays is either a focusing or defocusing of the laser. The resultant signal from the photo diode is the change of the pressure field recorded as changes in the intensity.

Using the lens model, we see that the quadratic phase term⁷ will lead to two more differentiations. Thus the fields measured are the third temporal derivative of the actual field. In what follows, the actual measurements are presented, and no signal processing has been performed on the measurements.

4. Experiment

4.1 Experimental model

The experimental model uses a point source, the transducer, to launch the pressure waves and a line detector, the acousto-optical system, to measure the changes in pressure. The theoretical model uses reciprocity to look at the situation as a set of line sources and a point detector. The line array is assumed to be a 21 by 21 element array arranged in a Cartesian grid. All the elements along X at a given Y (see Figure 1) are assumed to launch the same signal simultaneously. Thus 11 signals are created, and the data acquired by positioning the transducer at 21 locations.

The measurements are digitized, named and stored. After all the signals are acquired, they are assembled into the field of the simulated array. The elements are assumed to be point sources and separated by 3 mm center to center. The array is 6 cm square.

4.2 Experimental system and method

The experimental system is shown in Figure 1. The position control system has 6 degrees of freedom. The optical detection system consists of a HeNe continuous laser with a power of 5 mWatt. The intensity of the laser is detected by a fast photo - diode and the output of the diode digitized. A lens is used to project a virtual diode into the water near the phase grating created by the acoustic pulse.

Figure 1. The acousto-optical experimental system. The transducer is a broad bandwidth commercial unit with a 0.25 in diameter element and a nominal resonant frequency of 5.0 MHz. The laser is a 5 mWatt HeNe continuous beam unit. The lens is used to project the photo-diode into the water near the acoustic phase grating.

The acoustic system consists of an arbitrary waveform generator which is a fast digital to analog converter. Signals created in a computer are downloaded to it, and these signals are launched on demand. A power amplifier boosted the signals to about 30 volts maximum and powered the transducer. The transducer is a commercial unit with a nominal resonance of 5 MHz and a 0.25 inch diameter. For all practical purposes, it is a point source.

The time circuit consists of the control computer, which drives the whole experiment, the sync pulser and the transient digitizer. The control computer is a small personal computer running a command interpreter. It loads signals into the waveform generator, calls the proper signal up, positions the transducer relative to the optical detector, launches the wave into the water, and records the resulting diode signal. Each measurement is the result of 1000 pulses to improve the signal to noise ratio.

The transducer is moved along the Y direction for 21 positions. At each position in Y, the eleven waveforms are launched, as well as several control waveforms which are used to check the system. These were single frequency tonebursts both with a Gaussian taper along the array radius and with no taper. In all cases, the tonebursts agreed with the expectations of diffraction theory.

4.3 Experimental results

The measured results compared to the theoretical predictions at 25, 50 and 100 cm along Z are presented, as intensity maps, in Figure 2. The agreement between them is excellent. The data is simulated array reconstruction, but the theory is a linear one, so the technique is valid.

The horizontal axes represent 2.56 μ s in time or 0.384 cm in distance. The vertical axes represent -3 to +3 cm, the array aperture. Time increases from left to right, and downrange distance is represented by the figures from right to left. All intensities have been individually normalized to 1, so the comparison is a qualitative one.

The effective frequency of the pulse was determined by summing the spectral magnitudes of the individual array element signals, and integrating over frequency. The frequency which was higher than 87 per cent of the total energy, the 1.-exp(-2) point, was taken as the effective frequency. In this case the Rayleigh distance, for a continuous wave equivalent, is approximately 28 cm for the 6 cm array.

The LW beam has maintained its localization to more than 2 times this Rayleigh distance for this very crude, 1 dimensional array case. Results for 2 dimensional arrays have surpassed this result, yielding beams surpassing 10 times the equivalent Rayleigh distance.

The theoretical fields are constructed by adding the source signals, properly delayed, and then taking three time derivatives of the result. The excellent agreement of these fields to the measurements, as well as calibration measurements, show the high sensitivity of the acousto - optical detection method.

5. SUMMARY

The acousto - optical detection method has been applied to acoustic field measurements. This technique was used to avoid distortion in the measurements. The technique proved to be an accurate and sensitive method for measuring the pressure of the broad bandwidth pulsed sound field near the axis of the array. The measurements confirmed the predicted localization of the Localized Waves pulses.

6.ACKNOWLEDGMENTS

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Figure 2. Comparison of theory to experiment at 25, 50 and 100 cm. Time is left to right in all 6 pictures. The theoretical fields, above, are somewhat more narrow than the experimental cases, below. This corresponds to a loss of high frequency signal in the experimental cases. The field shapes and widths are in excellent agreement.

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