Remote Acoustical Mine Neutralization Using Back-Propagated Shock Waves

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LONG-TERM GOALS

The feasibility of using focused shock waves for mine neutralization requires detailed understanding of nonlinear wave propagation in water. This project investigates several fundamental issues of nonlinear acoustics when the primary source configuration is a discrete array of intense sources. Questions addressed through the theoretical analysis and an experimental effort concern the applicability of linear superposition and beamforming for performance predictions.

OBJECTIVES

The main objectives for this project include two fundamental aspects of nonlinear wave propagation from a discrete array. First, the question of linear superposition of nonlinear acoustic fields from discrete sources is investigated. Given independent fields from each source in a collection of sources, can these fields be superposed to predict the field from an array? The second objective investigates the nonlinear acoustic field produced by an array of discrete sources where beamforming is important. That is, can the initial phase of each element in the array be adjusted to provide a beamforming capability? Both theoretical and experimental research efforts were carried out where the experiments provide partial validation and confirmation for the conclusions of the theoretical work.

APPROACH

The theoretical analysis involved numerical computations based on an augmented Khokhlov-Zabolotskaya-Kuznetsov parabolic nonlinear wave equation (KZK). This equation assumes progressive wave propagation and includes the affects of thermoviscous absorption, diffraction, quadratic nonlinearity, and relaxation processes on the propagation. The KZK equation is expected to provide an accurate approximation for a nonlinear acoustic field provided the pressure does not exceed approximately 200 MPa anywhere within the spatial domain of the computation. This bound results from a requirement in the derivation of the KZK equation that the acoustic Mach number remains small (typically, less than 0.1). The KZK equation has been used to predict the pressure from unfocused and weakly focused circular piston transducers as well as spark-source lithotripters where the spark source is located at one of the foci of a ellipsoidal reflector.

Experimental confirmation of the KZK equation has concentrated on frequencies and dimensions that are inapplicable to the mine neutralization problem. Although these experiments confirm the general validity of the KZK equation, effects observed in the experiments can not readily be extrapolate to parameters appropriate to mine neutralization. Hence, controlled laboratory experiments at Boston University were performed at lower frequencies to further substantiate the KZK predictions.

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WORK COMPLETED

The theoretical effort in FY98 completed the required modifications of a computer code available at the Applied Physics Laboratory to accommodate an annular array configuration. This configuration permitted investigation of linear superposition and beamforming under conditions where nonlinear wave propagation is expected. The annular array geometry was chosen for its computational efficiency and the possibility of realizing such an array in a laboratory experiment. The computer code accepts an annular array that can contain an arbitrary number of concentric annular elements about a central piston element. The amplitude of each element and the phase relative to the center element is adjustable permitting essentially any finite pulse shape such as a short sine wave tone burst (see Figure 1) or an impulsive wave form generated by an explosive source (see Figure 2) provide the peak amplitude satisfied the above constraint.

Two features added to the numerical code were an artificial absorbing layer along the edge of the grid and adaptive time-step algorithms. These modifications significantly reduced computational requirements and execution times.

Nonlinear wave propagation requires a detailed set of physical parameters to describe the fluid. Various references provide empirical rules as functions of ambient pressure, salinity, and temperature of these physical parameters for fresh and sea water. These rules have been tabulated by Kargl (1998).

Experiments at Boston University have been completed and the results have been described by Edson and Roy (1998). Briefly, these experiments were conducted in filtered, deionized water. The dissolved gas content of the water was reduced to 85% of saturation to inhibit cavitation. The ambient pressure was approximately 1 atm, and the salinity of the water throughout the experiments was 0 ppt. Attempts to maintain a constant ambient temperature were not implemented. Each experiment started with an ambient temperature dictated by the laboratory temperature (nominally, 17 degrees Celsius).

In the experiments, the array consisted of a center circular element and six concentric rings. Each element was constructed from a 1-3 piezo-composite. The center frequency of the array was 480 kHz with a 210 kHz bandwidth. Experiments were conducted at 500 kHz. The surface area of an element was 18.85 cm^2 and the radius of the innermost element was 2.45 cm. A 0.03-cm gap separated adjacent elements, which were coplanar. The elements (and auxiliary electronics) were independent and isolated to reduce cross-talk and permit phasing of the array to adjust the depth of focus.

SCIENTIFIC/TECHNICAL RESULTS

Figure 1 compares experimental data from Boston University and the theoretical predictions of the KZK equation near the geometric focus of the seven-element array. The center frequency of the signal is 500 kHz, and the phase of each element is adjusted to produce a focal spot 0.24 m from the array face. During the experiments (Figure 1a), the source signal was a 10-cycle sine wave pulse with a exponential envelope while five cycles were used in the computations (Figure 1b). The peak source amplitude at the face of the array is 0.2 MPa. The fluid conditions correspond to approximately 1 atm ambient pressure, 17 degrees Celsius, and fresh water. Two curves are shown in each panel of Figure 1. The solid curve is the acoustic field when all the array elements are driven simultaneously but with an appropriate phase to produce the focusing. The dashed curve represents a linear superposition of the possibly nonlinear acoustic fields from the individual elements. This linear superposition neglects the nonlinear interactions between the independent acoustic fields. Figure 1 clearly demonstrates that a simple linear superposition of acoustics fields when nonlinearity becomes important breaks down. Hence, proper modeling must be performed to predict the nonlinear wave propagation from a discrete Array.

The Boston University experiments and the corresponding computations suggests that the KZK equation can be used to model the performance of a discrete annular array. However, the feasibility of predicting the performance of a discrete annular array that may be deployed in a mine neutralization scenario remains. Figure 2a shows the predicted acoustic field from a focused 32-element annular array with a one-meter radius aperture and geometric focus of 50 m. The two curves are the on-axis normalized pressures at 40 m from the array when the source amplitude is approximately 0.1 MPa. The source waveform is an impulse with a 4 ns rise time followed by a long exponential rarefaction. The solid curve is for fresh water and the dashed curve is for sea water where relaxation processes are included in the computations. Figure 2b shows the peak positive pressure along the acoustic axis. Figure 2c and 2d depict the pressure and the peak positive pressure along the acoustic axis from a weakly focused piston type source under the same conditions. Finally, $\tau = \omega t$ is a normalized retarded time where $\omega = 2\pi f$ and the frequency is f = 83.3 kHz.

Several features are evident in Figure 2. First, inclusion of the relaxation processes associated with magnesium sulfate and boric acid in sea water provides additional attenuation and dispersion. This is observed in Figures 2a and 2c by the slightly diminished amplitude to the sea water signal (attenuation) and the temporal spreading (dispersion) of the pulse. Second, the "kink" near 5 m in Figure 2b is a real affect and not a numerical artifact. The elements of the array are coplanar, and phased to provide focusing. This kink simply shows that the fields from the outer elements have not reached the acoustic axis of the array. The last feature is the amplitude of the second positive peak in Figures 2a and 2c. This peak is stronger for the annular array than for the focused piston transducer. Thus, a target can be subjected to two large positive pressure peaks from a single firing of a pulse-power array where the second peak may be larger than expected from a continuous single element transducer.

IMPACT FOR SCIENCE/SYSTEMS APPLICATIONS

Although the computations shown in Figures 1 and 2 consider only a single array geometry at a rather short range, the implications are clear. Any analyses of current or future mine countermeasure (MCM) systems that use intense acoustic fields as the primary neutralization mechanism must properly account for nonlinear wave propagation. The Water Hammer Program sponsored by DARPA (see below) suggests that the peak pressure at a mine should be at least 13.8 MPa. When standoff distances of a few hundred meter are considered, it is clear an intense acoustic field will suffer significant energy losses to thermoviscous absorption, diffraction, and nonlinear generation of higher harmonic as well as relaxation processes due to dissociation of certain chemical species in seawater. Hence, the source level at an array will typically exceeded the source levels chosen for the computations shown. However, the underlying assumptions leading to the KZK equation suggests that it can be used at these source levels.

TRANSITIONS

Although the annular array geometry permits investigation of superposition and beamforming, it is limited to an axisymmetric situation. That is, only the depth of focus can be changed be phasing the array. The ability to steer the beam off the axis of symmetry is not present. KZK equations for a rectangular aperture and a line source have been developed. These equations allow investigate of other geometries where beam steering can be performed.

RELATED PROJECTS

Remote Acoustical Mine Neutralization: Student Support is an Augmentation Awards for Science and Engineering Research Training grant (AASERT) which provides funding for a graduate student. The goals of this grant include investigations of time reversal through modeling and experiments. A finite-difference time-domain simulation has been developed for a nonlinear, absorbing, inhomogeneous wave equation.

The Water Hammer program, funded by DARPA, under the auspices of Dr. Theo Kooij seeks to use pulse power technology to neutralize mines. The theoretical techniques developed under the present program have direct impact on the wave propagation from a Water Hammer source.

REFERENCES

P. Edson and R. A. Roy, Nonlinear Wave Propagation from a Discrete Annular Array, Tech. Rep. AM-98-038, (Dept. of Aerospace and Mech. Eng., Boston University, 1998).

S. G. Kargl, Nonlinear Wave Propagation with Implications for Mine Neutralization, Tech. Rep. APL-UW TR9803, (Applied Physics Laboratory, University of Washington, 1998).

PUBLICATIONS

S. G. Kargl, Nonlinear Wave Propagation with Implications for Mine Neutralization, Tech. Rep. APL-UW TR9803, (Applied Physics Laboratory, University of Washington, 1998).

P. Edson and R. A. Roy, Nonlinear Wave Propagation from a Discrete Annular Array, Tech. Rep. AM-98-038, (Dept. of Aerospace and Mech. Eng., Boston University, 1998).

S. G. Kargl, R. A. Roy, and P. Edson, “Nonlinear wave propagation from a discrete annular array: theory,” in Proc. *Joint meeting of the Inter. Congress on Acoust. and the Acoust. Soc. of Amer.*, (Seattle, WA, 1998), 531.

P. Edson, R. A. Roy, and S. G. Kargl, “Nonlinear wave propagation from a discrete annular array: experiments” in *Proc. Joint meeting of the Inter. Congress on Acoust. and the Acoust. Soc. of Amer.*, (Seattle, WA, 1998), 533.

S. V. Babenkova, V. A. Khokhlova, and S. G. Kargl, “Nonlinear effects in the paraxial region of diffracting sound beams radiated by cylinder sources” in *Proc. Joint meeting of the Inter. Congress on Acoust. and the Acoust. Soc. of Amer.*, (Seattle, WA, 1998), 1699.

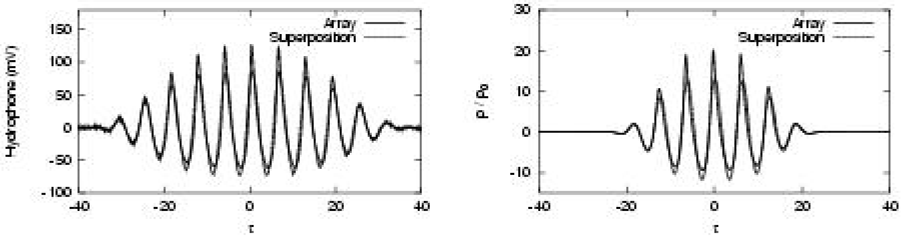

Figure 1.

(a) Boston University experimental data. The source amplitude is 300 kPa and the array is phased to focus at 0.24 m. (b) KZK computations. The physical conditions of the experiment are used to compute the propagated wave except for the pulse.

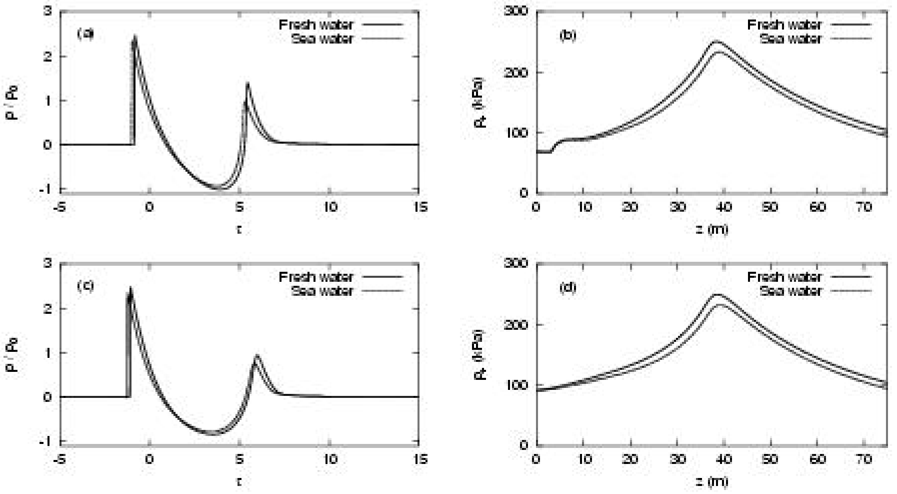

Figure. 2

Comparison of the nonlinear wave propagation of an impulsive source in fresh and sea water. (a) Pressure signature from a 32-element array at 40 m. (b) Peak positive pressure along the acoustic axis of the array. (c) Pressure signature from a weakly focused piston transducer at 40 m. (d) Peak positive pressure along the acoustic axis of the focused piston transducer.