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A plane wave source with minimal harmonic distortion for investigating nonlinear acoustic properties

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Abstract

The objective of this investigation is to introduce and validate a practical ultrasound source to be used in the investigation of the nonlinear material properties of liquids and soft tissues studied *in vitro*. Methods based on the progressive distortion of finite amplitude ultrasonic waves in the low megahertz frequency-range are most easily implemented under the assumption of plane wave propagation. However, achieving an approximately planar ultrasonic field over substantial propagation distances can be challenging. Furthermore, undesired harmonic distortion of the ultrasonic field prior to insonification of the specified region of interest represents another serious limitation. This paper introduces an approach based on the use of the ultrasonic field emanating from a stainless-steel delay line. Both simulation and direct experimental measurement demonstrate that such a field exhibits relatively planar wavefronts to a good approximation (such that a 3 mm diameter receiver would be exposed to no more than 3 dB of loss across its face) and is free from the significant harmonic distortion that would occur in a conventional water path.

I. INTRODUCTION

In previously published ultrasonic experiments designed to measure the intrinsic nonlinear parameter, β , interpretation of the measured data was frequently simplified by approximating the insonifying ultrasonic field as a plane wave over the region of interaction with the sample under investigation.^{1–12} A number of methods to realize this approximation have been utilized and, in general, rely on careful positioning of the sample in a region of the ultrasonic field where the diffraction pattern can be approximated as planar, such as the extreme near field,^{1, 2} the natural focus,^{3–5} or the far field.⁶ Estimates of the nonlinear parameter can be determined from finite amplitude measurements of the level of harmonic distortion in the ultrasonic signal after propagation through either a series of thicknesses of a sample^{1, 2} or a single sample.^{3–12}

One method that has been used successfully in our Laboratory is to affix a stainless-steel delay line to a transmitting transducer such that the output field from the delay line satisfies a plane wave approximation.^{3, 4} An advantage with this approach is that the high sound velocity in the stainless-steel (approximately four times faster than in water) permits the ultrasonic beam to satisfy the plane wave approximation in a relatively short distance, rather than after traveling a relatively long (possibly prohibitively long) path. Furthermore, this method reduces the generation of undesired harmonic distortion arising from propagation to the sample under investigation, as propagation within the stainless steel delay line results in only a negligible amount of finite amplitude distortion, eliminating the need for physical attenuators in the propagation path.⁶

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In the current investigation, scanned hydrophone pseudo-array measurements and numerical simulations were used to investigate the applicability of a plane wave approximation for an ultrasonic pulse emanating from a stainless-steel delay line and to assess the amount of harmonic distortion generated from propagation in the delay line. Hydrophone measurements of the ultrasonic field in water were conducted in a meridian plane and compared with the results from simulations of the diffracting finite amplitude field associated with a 12.7 mm diameter contact transducer propagating either a 7 MHz or a 4 MHz tone burst through a 46.4 mm steel delay line and 25.0 mm of water.

II. EXPERIMENTAL METHODS

A. Experimental Setup

The delay line used in this experiment was machined from an 88.9 mm diameter cylinder of type 304 stainless-steel. The faces of the cylinder were machined flat and parallel, and polished smooth, producing a delay line of 46.4 mm in length as measured by Vernier calipers. A 12.7 mm diameter, broadband, 10 MHz center frequency contact transducer (Panametrics V111, Waltham, MA) was bonded to one face of the stainless-steel cylinder using a thin, uniform layer of vacuum grease and held in contact with a plastic (Delrin™) fixture, as illustrated in Fig. 1. This created a watertight seal and enabled the contact transducer-delay line assembly to be submerged into a water tank for hydrophone characterization of the transmitted ultrasonic field.

The first ultrasonic frequency (7 MHz) used in this investigation was chosen such that the ultrasonic beam's diffraction pattern would be entering the natural focus as the pulse exited the delay line apparatus. This frequency was determined using the formula for the near field distance, given by,

$$\text{Near Field Distance} = \frac{D^2}{4\lambda} \left[1 - \left(\frac{\lambda}{D} \right)^2 \right], \quad (1)$$

where D is the diameter of the source transducer and $\lambda = c_0/f$ is the ultrasonic wavelength.¹³ The speed of sound in the stainless-steel, c_0 , was experimentally determined to be 5.73 mm/ μ s using a contact transducer in a pulse echo mode to measure the round-trip time of flight inside the stainless-steel delay line. To position the natural focus of the ultrasonic field just after emerging from the stainless-steel delay line, as defined by Eq. 1, a center frequency of 7.0 MHz was chosen for the narrowband transmitted signal. For this study, the transmit transducer was driven with a 4.0 μ s duration tone burst gated from a 7.0 MHz continuous-wave signal oscillator (Hewlett-Packard 606B, Palo Alto, CA) and amplified with a 50 dB amplifier (ENI 240L, Rochester, NY). The gating was accomplished with a pulse generator (Hewlett-Packard 8112A) in conjunction with two mixer/modulators in series (Hewlett-Packard 33125).

In addition, a lower frequency, 4 MHz, was chosen to test the applicability of this specific delay line for making measurements within the focal zone to far field transition regime of the ultrasonic field. In this case, a 12.7 mm diameter, broadband, 5 MHz center frequency contact transducer (Panametrics V109) was utilized. The transducer was driven by a 4.0 μ s tone burst at 4.0 MHz from a function generator (Hewlett-Packard 8116A) in conjunction with a 50 dB radiofrequency amplifier (ENI 240L) and a passive 6.4 MHz low pass filter.

B. Measurements

To characterize the ultrasonic pressure field of the system, the transducer and delay line were positioned in a water tank with the ultrasonic beam aligned along the X -axis of a motion control system (Aerotech Unidex 511, Pittsburgh, PA). The temperature of the water was monitored

using a thermistor (Omega OL-710, Stamford, CT) connected to a thermometer (Omega 5831A). The temperature of the water tank was maintained at $23.8^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$ and $21.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ during the measurements of the 7 MHz and 4 MHz signals, respectively. A membrane hydrophone (Sonic Industries, Model 804, now Sonora Medical Systems, Longmont, CO) was scanned in a rectangular, 81 by 57 pseudo-array using a uniform step size of 0.25 mm (20 mm by 14 mm total grid size) to map out the ultrasonic field in the meridian (X - Y) plane. The hydrophone calibration was performed by the manufacturer using a reference hydrophone that had been calibrated at the National Physical Laboratory in the United Kingdom. The resulting radiofrequency signals output from the hydrophone preamplifier were digitized with an eight-bit resolution oscilloscope (Tek 2440, Beaverton, OR) for the 7.0 MHz acquisitions, and a Tektronix 5052B for the 4.0 MHz acquisitions). Data could be acquired with the membrane hydrophone positioned as close as 4.0 mm to the face of the steel cylinder while avoiding reverberations between the steel cylinder and the hydrophone. The received waveforms were signal averaged in the time domain to improve the signal-to-noise ratio for data acquired for both the 7.0 MHz and 4.0 MHz systems. The values of the acoustic pressure at the fundamental and harmonic frequencies were determined by determining the voltage amplitude of each spectral component of the signal averaged waveform and referring to the pressure-voltage calibration data provided by the hydrophone manufacturer.

III. SIMULATIONS

Simulations were carried out using a Burgers' equation enhanced angular spectrum approach.^{14–16} This approach permits the modeling of the propagation and the harmonic distortion of a diffracting ultrasonic signal as it propagates through the different propagation media (steel and water). Simulations were performed for the two fundamental frequencies employed experimentally (4 MHz and 7 MHz). Effects of attenuation were taken to be negligible for both the steel and water at these frequencies. The nonlinear parameter β was taken to be 3.5 for both water and stainless-steel. (A literature search for similar metals yielded values for β ranging from 2 to 4.5 and thus the nonlinear parameter for stainless-steel was taken to be 3.5 for this simulation).¹⁷

The predictions from simulation for the normalized particle velocity amplitudes of the 7 MHz fundamental ($1f$) component are depicted in Fig. 2(a). A grayscale image of the magnitude for the meridian plane slice is shown in the top panel and the profile corresponding to the values of the field on the beam axis is shown in the bottom panel. As depicted in Fig. 2(c), the beam is propagating from left to right, first through the stainless steel delay line and then through 25 mm of water. The vertical dashed line indicates the boundary between steel and water. Similarly, the nonlinearly generated 14 MHz second harmonic ($2f$) component of the particle velocity obtained from simulation is displayed in Fig. 2(b). In both cases, the pressure has been normalized to the initial fundamental pressure at the face of the transducer.

Fig. 3 presents the corresponding results for the 4 MHz simulation. For both simulations the second harmonic amplitude along the propagation axis is observed to grow linearly as a function of propagation distance in the water region. This is consistent with the second order (weakly nonlinear) approximate form of the Fubini solution.¹⁸

IV. EXPERIMENTAL MEASUREMENTS AND RESULTS

A. 7 MHz Study

Fig. 4 shows the measured amplitudes of the 7 MHz fundamental ($1f$) and 14 MHz harmonic ($2f$) components in the meridian plane pseudo-array scan for the identical waterpath region shown in the simulations presented in Figs. 2(a) and (b). The grayscale is normalized in each image such that black represents the maximum amplitude and white is zero. Because one goal

of this work is to produce a valid approximation to a plane wave over an experimentally useful area, the size of a 3 mm diameter receiving transducer is represented by hash marks on the right hand side of each of the four images in Fig. 4.

Fig. 5(a) illustrates the power along the axis of propagation as a function of distance for each of the four panels in Fig. 4. The curves represent the measured power relative to the fundamental at the left edge of the plot (axial distance of 50 mm). The measured pressure values for the fundamental and second harmonic at an axial distance of 70 mm were 53.2 kPa and 2.2 kPa, respectively. Fig. 5(b) illustrates the predicted and measured transverse profiles of the power in the fundamental frequency at an axial distance of 70 mm. Fig. 5(c) shows this comparison for the second harmonic portion of the signal.

B. 4 MHz Study

Fig. 6 shows the measured amplitudes of the 4 MHz fundamental (1f) and the 8 MHz second harmonic (2f) components of the transmitted ultrasonic beam in the meridian plane. These are displayed along with the simulation results of Figs. 3(a) and (b). For each panel, the image is normalized so that black represents the maximum amplitude and white represents zero. Again, hash marks are present on the right side of each panel to indicate the receiving size of a 3 mm diameter transducer.

Fig. 7 shows orthogonal one-dimensional slices of the measured and simulated ultrasonic beams detailed in Fig. 6. In Fig. 7(a), the power along the axis of propagation is shown as a function of axial distance for each of the four panels found in Fig. 6. Each curve is normalized to the measured power of the fundamental at the left edge of the plot, which is at 50 mm from the source transducer. The values of the pressure for the fundamental and second harmonic were measured at a distance of 70 mm from the transducer, and were 23.6 kPa and 228 Pa, respectively. Fig 7(b) and (c) illustrates a comparison of the simulation with the measured results for a transverse profile taken at an axial distance of 70 mm for the fundamental and second harmonic, respectively.

V. DISCUSSION

Overall, good agreement is observed between the measured and simulated cross sections of the ultrasonic fields. For the 7 MHz case, the measured magnitude and features of the transverse cross sections for the fundamental (1f) component appear to be relatively constant over the 20 mm range of axial propagation distances investigated. This agrees with the simulation (Fig. 2), where the amplitude of the 7 MHz fundamental is observed to vary by only 0.13 dB along the axis in the region of the water filled sample chamber. The hydrophone measurements of the on-axis power, for both the fundamental (7 MHz) and second harmonic (14 MHz) components, are in good agreement with predictions from the simulation, as can be seen from Fig. 5(a). Figs. 5(b) and (c) indicate that the field varies by less than 3 dB for the fundamental and less than 6 dB for the second harmonic across a 3 mm diameter. The relatively good agreement between the experimental measurements and predictions from the simulation support the validity of a plane wave approximation to the field.

Transmission of a narrowband 4 MHz signal yielded similar results. The fundamental component of the signal remains relatively constant across the measured range of axial propagation. As seen in Fig. 3, the amplitude of the fundamental component decreases by only 0.9 dB over the 20 mm axial range of the figure. Examination of Fig. 7(b) and (c) indicates that the ultrasonic power varies by less than 0.75 dB for the fundamental and less than 1.5 dB for the second harmonic across the 3 mm diameter that is marked by the vertical dashed lines. In comparison with the 7 MHz case, where the 3 dB width of the ultrasonic beam was only 3

mm, the 3 dB width for the 4 MHz case has increased to over 6 mm. This indicates a wider region over which a plane wave approximation is valid.

There is, however, a drawback to using the far field region of the ultrasonic beam to generate a wider plane wave region. Due to the nature of the far field, the ultrasonic amplitude of the fundamental signal will not be as large as what is found in the focal zone, so there will be a correspondingly lower rate of harmonic generation. In comparison with the 7 MHz study illustrated in Fig. 2 and 3, the final amplitude after 25 mm of propagation in water is smaller for the 4 MHz case, although in both cases the initial harmonic is negligible. Additionally, the nonlinear generation of the second harmonic is linearly dependent upon the frequency in the weakly nonlinear regime, and thus using a lower frequency reduces the rate of generation of the second harmonic distortion.¹¹ The decrease in the signal-to-noise ratio for the second harmonic can be seen in Fig. 6. Nevertheless the far field approach does allow for a certain amount of flexibility because an experiment can be adjusted to give a plane wave over the field depth needed for propagation through a sample while maintaining the necessary signal to noise ratio needed for measuring the harmonic distortion of a pulse.

An additional benefit of the delay line lies in the lack of nonlinear generation within the steel, compared to propagation in water. To understand this, consider the shock formation distance for plane wave propagation:

$$\bar{x} = \frac{\rho_0 c_0^3}{\beta \omega_0 p_0} \quad (2)$$

where ρ_0 is the density, c_0 is the sound speed, β is the coefficient of nonlinearity of the medium, and ω_0 and p_0 are the angular frequency and pressure of the incident pulse, respectively. The density of steel is roughly eight times that of water, and the sound velocity is about four times that of water. The nonlinear parameters of steel and water are approximately the same, as discussed earlier. Thus, calculation of the ratio of shock formation distances for steel and water reveals that the shock formation distance in steel is much larger than that for water. Therefore, the relative amount of nonlinear distortion is significantly less in steel. In addition, propagation to a given portion of the diffraction field in steel is accomplished in one-quarter the propagation distance in water; nonlinear generation is reduced further by this reduction in path length. Thus, the distortion in a typical length delay line is negligible compared to the distortion in the same diffractive region in a water path. This is illustrated in both Fig. 2 and 3, which indicate that the simulations predict that the ultrasonic signal has virtually no amplitude in the second harmonic while the fundamental propagates through the steel. This is also affirmed in the experimental work, in which a very small amount of distortion is measured in the signal when measured as close to the face of the delay line as possible. For the 7 MHz study, the measured amplitude in the second harmonic was 40 dB down from the amplitude in the fundamental signal, and for the 4 MHz study this difference increased to 50 dB.

The use of this delay line apparatus has other practical advantages. One primary benefit is that the absence of transmitted harmonics obviates the need to employ physical means of attenuation to reduce unwanted harmonic signals. The introduction of such materials, such as attenuating media and quarter-wave plates, can cause signal loss in the fundamental frequency.^{6, 19} Another benefit of the delay line is that it can be used in other types of nonlinearity experiments. If the whole assembly is oriented vertically and a chamber wall for containing fluid samples is attached, measurements of the nonlinearity parameter based on a pullback approach can be performed.¹⁻⁴ Such a setup benefits from the plane waves generated as well as the lack of transmitted harmonics, but permits the receiving transducer to be manually translated in the fluid medium of interest.⁴

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Figure 1.

Diagram of the stainless-steel delay line apparatus. The transducer is a 12.7 mm diameter contact transducer, held in place with a plastic fixture to the face of the steel cylinder. Simulation of the 7 MHz fundamental ($1f$) field component is shown inside the delay line.

Figure 2.

Simulation of the diffraction pattern through a 304-stainless steel delay line into lossless water medium, for (a) the 7 MHz fundamental component, and (b) the 14 MHz second harmonic. The top portion of each figure component illustrates the magnitude of the meridian plane slice of the field (black is the maximum amplitude and white is zero). The bottom portion of each component shows the amplitude along the propagation axis of the beam. The phase velocity used in the simulation corresponds to measured values of 5.73 mm/ μ s in steel and 1.48 mm/ μ s in water. The particle velocity amplitudes are normalized to that of the fundamental component at zero axial distance.

Figure 3.

Simulation of the diffraction pattern through a 304-stainless steel delay line into lossless water medium, for (a) the 4 MHz fundamental component, and (b) the 8 MHz second harmonic, in a manner analogous to Figure 2.

Figure 4.

Comparison of expected beam pattern from simulation (left) with hydrophone measurement of the field (right) in a meridian plane beginning 4 mm beyond the steel-water interface, for a 7 MHz fundamental signal. The separation between the hash marks on the right side of each graph corresponds to the 3 mm diameter of a receiving transducer.

Figure 5.

(a) Comparison of hydrophone measurements and simulation results, for both the fundamental and second harmonic, in the axial direction. (b) The normalized transverse profile for the 7 MHz fundamental, 70 mm away from a 12.7 mm diameter piston source, propagating through 46.4 mm of stainless steel and 23.7 mm of water. (c) Normalized transverse profile of the second harmonic amplitude at the same location as (b).

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Comparison of expected beam pattern from simulation (left) with hydrophone measurement of the field (right) in a meridional plane beginning 4 mm beyond the steel-water interface, for a 4 MHz fundamental signal. The separation between the hash marks on the right side of each graph corresponds to the 3 mm diameter of a receiving transducer.

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