Experimental Validation of Computational Models for Large-Scale Nonlinear Ultrasound Simulations in Heterogeneous, Absorbing Fluid Media

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Abstract. To increase the effectiveness of high intensity focused ultrasound (HIFU) treatments, prediction of ultrasound propagation in biological tissues is essential, particularly where bones are present in the field. This requires complex full-wave computational models which account for nonlinearity, absorption, and heterogeneity. These models must be properly validated but there is a lack of analytical solutions which apply in these conditions. Experimental validation of the models is therefore essential. However, accurate measurement of HIFU fields is not trivial. Our aim is to establish rigorous methods for obtaining reference data sets with which to validate tissue realistic simulations of ultrasound propagation. Here, we present preliminary measurements which form an initial validation of simulations performed using the k-Wave MATLAB toolbox. Acoustic pressure was measured on a plane in the field of a focused ultrasound transducer in free field conditions to be used as a Dirichlet boundary condition for simulations. Rectangular and wedge shaped olive oil scatterers were placed in the field and further pressure measurements were made in the far field for comparison with simulations. Good qualitative agreement was observed between the measured and simulated nonlinear pressure fields.

INTRODUCTION

In high intensity focused ultrasound (HIFU) treatments, a thermal dose is delivered to a target region to induce cell death [1]. In order to deliver the required dose to the target volume effectively, particularly where there are different tissues such as bones located in the field, it is necessary to know how the sound propagates in the tissues of the body and where the focus of the acoustic field will be located. Aberrations of the acoustic field caused by the interaction of the sound with tissues of different acoustic properties in the body render simple propagation models ineffective for predicting the location of high intensity regions of the field. More complex numerical simulations that can predict ultrasound propagation in heterogeneous biologically relevant media are thus an essential requirement for planning of these treatments and several have been reported in the literature [2]–[4]. Validation of these models is essential in ensuring the underlying assumptions are correct and to identify sources of uncertainty when the models are applied to individual patients. For these complex cases, there is a paucity of analytical solutions with which to validate models, and so obtaining accurate experimental data is therefore essential for model validation. However, accurate measurement of complex nonlinear acoustic fields is non-trivial as there are many sources of uncertainty, for example alignment errors, the sensitivity and directivity of sensors, perturbation of the field by the measurement equipment, and variation in environmental conditions, among others.

Here, a full-wave nonlinear ultrasound model accounting for heterogeneities and power law absorption which forms part of the open source k-Wave MATLAB toolbox [4] is used to simulate the acoustic field. Previously, experimental validation of k-Wave has been performed for nonlinear wave propagation in a homogeneous medium [5]. In this work, we aim to establish methods for acquiring the experimental data required for model validation in heterogeneous media. This paper presents preliminary measurements which form an initial validation of k-Wave for simulating non-linear ultrasound propagation in a heterogeneous fluid medium with simple geometric scatterers.

METHODS

Experimental Methods

Experiments were performed in a 60 × 60 × 100 cm tank of degassed, deionised water. The acoustic field was generated by a single element focused bowl transducer (H151, Sonic Concepts, Bothell, WA, USA). The transducer had an active area diameter of 64 mm and focal length of 99 mm. The transducer was driven at a frequency of 1.1 MHz with a 4 cycle burst at a drive level sufficient to generate harmonic content in the focal region of the field (~79 V peak to peak).

The input signal was generated by an Agilent 33522A Arbitrary Waveform Generator (Agilent, Berkshire, UK) and amplified by an E&I A075 RF power amplifier before transmission to the transducer via an impedance matching network. The drive signal was measured using a Tektronix TPP0850 oscilloscope probe and Tektronix DPO5034B Digital Phosphor Oscilloscope (Tektronix, UK Ltd., Berkshire, UK).

The acoustic signal was measured using a calibrated 0.2 mm PVDF needle hydrophone (Precision Acoustics Ltd., as above) connected to the oscilloscope via a 50 Ω shunt. The hydrophone position was controlled by a software controlled 3-axis positioning system (Precision Acoustics Ltd., Dorchester, UK), which automatically acquired and logged the waveforms. Water temperature was monitored via the software using a thermocouple probe (USBTC-01, National Instruments Corporation Ltd., Berkshire, UK).

Medium heterogeneities in the acoustic field were formed of rectangular (24.5 mm thick) and wedge (26 – 34 mm thick) shaped Perspex containers with 13 μm Mylar (ES301130, Goodfellow Cambridge Ltd., Huntingdon, UK) windows filled with olive oil (O1514, Sigma Aldrich Company Ltd., Dorset, UK). The containers were sufficiently large laterally so that the walls were outside the acoustic field. The containers were held in the acoustic field by two optical posts attached to an optical breadboard mounted on top of the tank (see Fig. 1). The transducer was also rigidly mounted to the breadboard to ensure a fixed alignment and positioning of the scatterers.
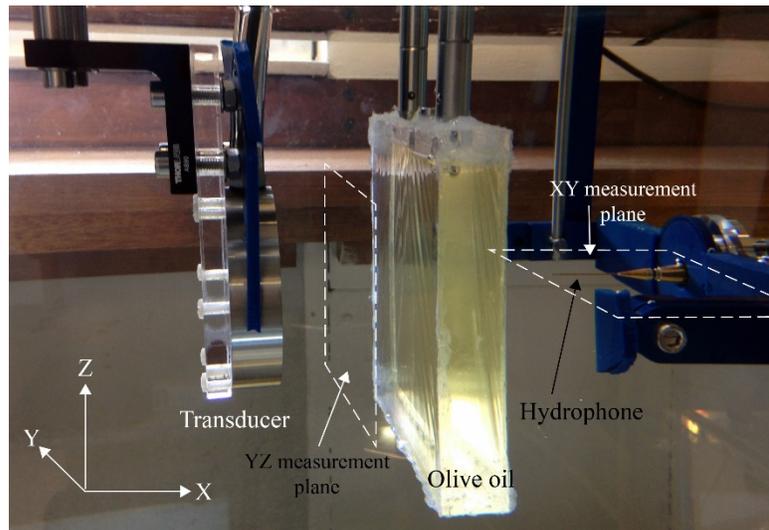
FIGURE 1. Experimental configuration; a YZ input plane was measured close to the transducer, an olive oil scatterer was inserted between the transducer and the hydrophone and an XY plane was measured in the far-field.

The acoustic signal was first measured in water over a plane perpendicular to the beam axis at a distance of 40 mm from the base of the transducer with 0.15 mm steps in the Y and Z directions covering an area of 48 mm by 48 mm. The acquired voltage waveforms over the measurement plane were converted to pressure using the known frequency dependent hydrophone sensitivity and used as a Dirichlet boundary condition for the k-Wave simulations. For measurements made with scatterers in the field, alignment of the transducer and hydrophone was first performed under free-field conditions. The transducer to hydrophone distance was calculated from the time-of-flight at the focus of the field. The oil was then inserted between the transducer and the hydrophone in the prefocal region. The experimental configuration is shown in Fig. 1. Field measurements were performed in the far-field in a plane lying

along the beam axis (XY). This covered an area of 30 mm by 40 mm (Δx = 1 mm, Δy = 0.15 mm) for the rectangular scatterer and 40 mm by 80 mm (Δx = 1 mm, Δy = 0.2 mm) for the wedge shaped scatterer.

Computational Methods

Simulations of the acoustic field were performed using the open-source k-Wave MATLAB toolbox which solves a generalised form of the Westerwelt equation accounting for nonlinearity, heterogeneities, and power law absorption using a k-space pseudospectral method [4]. A spatial step size of 0.15 mm and temporal step size of 40 ns was used (giving a maximum supported frequency of 4.97 MHz). Simulations were run using domain sizes of up to 1024×384×384 grid points on a compute server with 2 × 8-core Xeon E5-2650 2.0 GHz CPUs, and 256 GB of 1600 MHz DDR3 memory. Compute times were on the order of 1 hour. The measured input planes were used as a Dirichlet boundary condition and the heterogeneous medium properties were defined based on the experimental geometry. The attenuation coefficient, speed of sound, and nonlinearity parameter (B/A) of the oil were taken as 0.125 dB cm^{-1} MHz$^{-1.68}$, 1443 ms^{-1} [6] and 11.1 [7], respectively. The attenuation coefficient of water was 2.17x10^{-3} dB cm^{-1} MHz^{-2}, B/A was 4.96 [8], and the temperature dependent sound speed was calculated using Marczak's 5th order polynomial [9].

RESULTS AND DISCUSSION
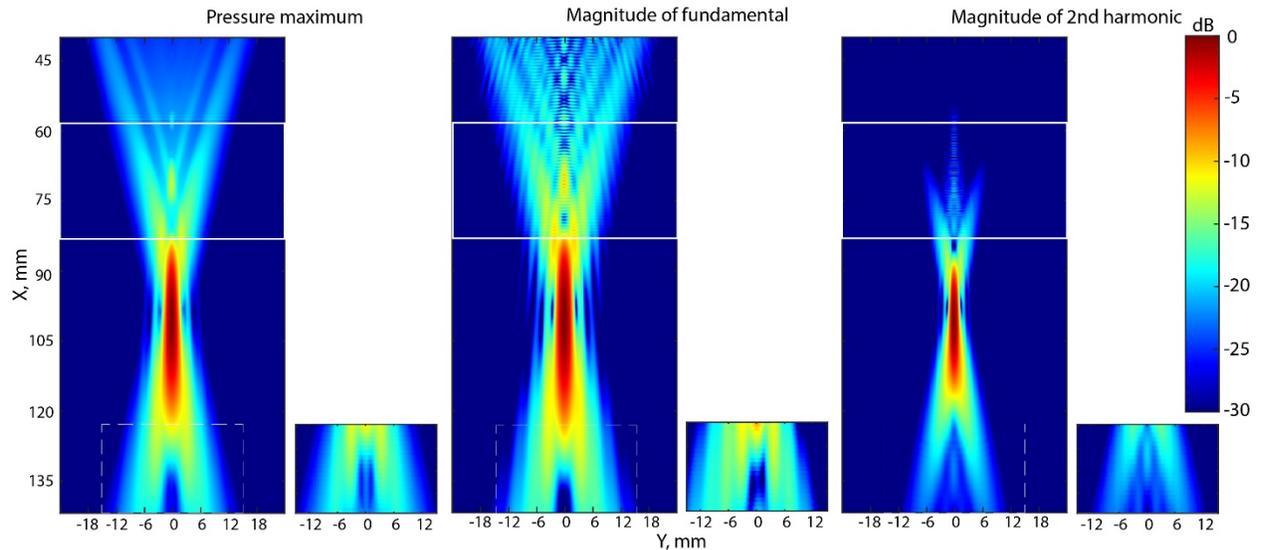
FIGURE 2. Comparison of simulated (large panels) and measured (small panels) maximum pressure, magnitude of the fundamental frequency, and magnitude of the 2nd harmonic with the rectangular oil scatterer (denoted by solid white lines) placed in the acoustic field.

A comparison was made between the measured and simulated acoustic fields for both the rectangular and wedge shaped scatterers. The maximum pressure in the simulated and measured data was calculated from the maximum pressure in the time domain waveforms at each spatial position. The pressure magnitude at the fundamental and harmonic frequencies was calculated as the value of the frequency spectrum of the time domain waveforms at the frequencies of interest at each point in the domain. Good qualitative agreement between the maximum pressure and the harmonics in the measured and simulated fields can be seen in both cases. Figure 2 shows the comparison between the maximum pressure, magnitude of the fundamental frequency, and the magnitude of the 2nd harmonic with the rectangular oil scatterer in the field. Figure 3 shows the equivalent data for the wedge shaped oil scatterer. In this data, the postfocal maximum can been seen in both the measured and simulated fields. The structure in the side lobes is also visible in the far-field in both the measured and simulated data. Shifting of the position of the focus can be seen relative to the field in water, especially for the wedge shaped scatterer where an angular offset in the field can be seen. Reflections at the water/oil interfaces are also visible. There was also good agreement of the 3rd and 4th harmonics (data not shown).
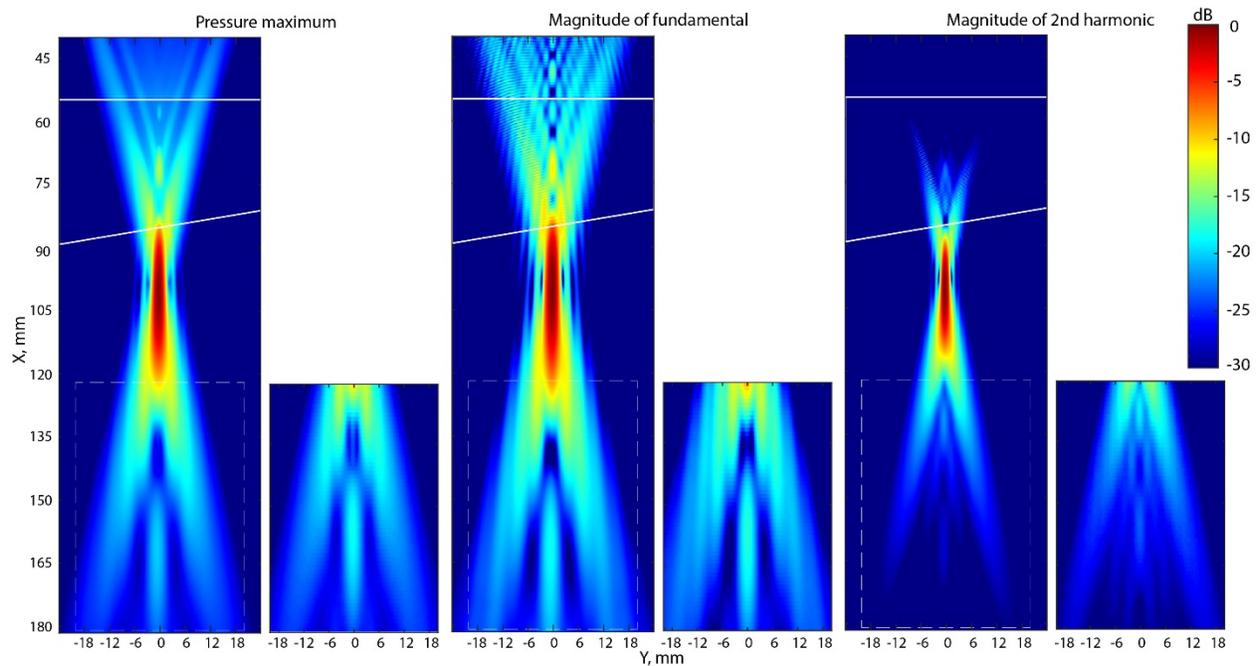
FIGURE 3. Comparison of simulated (large panels) and measured (small panels) maximum pressure, magnitude of the fundamental frequency, and magnitude of the 2nd harmonic with the wedge shaped oil scatterer (denoted by solid white lines) placed in the acoustic field.

CONCLUSIONS AND FURTHER WORK

Preliminary measurments for the validation of the k-Wave toolbox have been performed for a nonlinear field in a heterogeneous and absorbing fluid media. Good qualitative agreement between the measured and simulated data was obtained for both the rectangular and wedge shaped scatterer. Due to measurement constraints, the experimental validation planes presented here were restricted to a small region of the field. In future work, larger experimental data sets will be acquired more extensively covering the field. Further work is also required to fully quantitatively validate the simulations against measurements. The difference in sound speed between olive oil and water is not large and the oil is not strongly attenuating, the field was therefore only weakly perturbed. Further validation will be performed using liquid scatterers with a range of sound speeds and attenuation coefficients and air inclusions in to order increase perturbations of the field.

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