Nonlinear distortion of high-intensity ultrasound holographic patterns

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Abstract. High-intensity focused ultrasound (HIFU) is an emerging non-invasive therapeutic technology that has the potential to treat a wide range of medical disorders. By precisely focusing the ultrasonic energy, HIFU can heat up, destroy, or change target tissue. Acoustic holograms have been introduced as a novel and cost-effective method for creating elaborate and highly precise ultrasound fields. In HIFU, the linearity assumptions are no longer valid and will result in significant errors in the predicted sound field. The pseudospectral method was used to perform homogeneous three-dimensional nonlinear acoustic simulations. It will be shown that the nonlinear distortion leads to significant effects on the spatial distribution of the ultrasound field. The peak positive pressure and heat deposition become highly localized. While nonlinear effects flatten the peak negative pressure distribution with minimal and are shown to be vital for correctly estimating cavitation zones.

Introduction

Acoustic holograms are used for constructing elaborate focused ultrasound (FU) fields. By storing the phase information of the desired wavefront using a 3D-printed thickness map, the desired complex acoustic pressure field can be constructed by a single acoustic source. As the acoustic intensity increases, nonlinear effects become prominent leading to distorted and asymmetric waveforms. Studies that highlight the interaction of complex physics between the constructed holographic sound field and nonlinearities are absent. Here, the pseudospectral method is used to perform three-dimensional nonlinear acoustic simulations to investigate the evolution of modulated ultrasound field produced by an acoustic hologram as the acoustic intensity increases. The numerical model solves a set of coupled partial differential equations equivalent to a generalized Westervelt equation. The spatial pattern of the peak positive pressure, peak negative pressure, intensity, heat deposition, and cavitation zones were studied for a range of source pressure levels.

Results and discussion

The simulations were initiated with a linear sound field using a source pressure amplitude of $P_0 = 0.1$ MPa. The source amplitude was then increased to $P_0 = 1.8$ MPa to study the effects of rising nonlinearties on the sound field. As a result, the sinusoidal shape is distorted to a steeper waveform as the wave propagates further. Harmonics at integer multiples of the fundamental frequency are generated as a result of waveform distortion. Furthermore, diffraction effects cause a relative phase shift in the harmonics with respect to the fundamental component, resulting in an asymmetric waveform and a discrepancy between the peak positive pressure and the peak negative pressure as shown in figure 1. The peak positive pressure and heat deposition

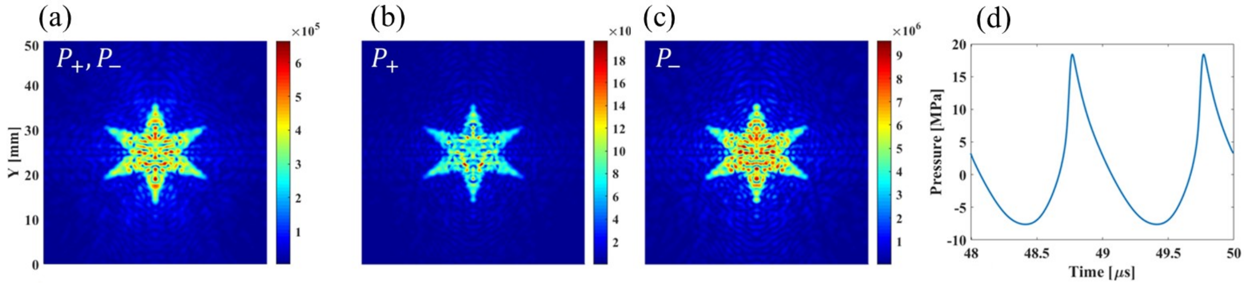

Figure 1: The distributions of linear amplitude [Pa] (a) at the target plane for a source pressure of $P0 = 0.1$ MPa. Positive pressure [Pa] (b), negative pressure [Pa] (c) distributions at the target plane for a $P0 = 1.8$ MPa source pressure and time waveform of the maximum positive pressure point (d).

become highly localized. Harmonic generation causes the heat deposition distribution to become extremely confined, with a nonuniformity index of 700%. While nonlinear effects flatten the peak negative pressure distribution and are shown to be vital for correctly estimating cavitation zones. Linear propagation predicts larger cavitation zones due to the higher gain of the linear negative pressure. Our findings guide the informed use of acoustic holograms in high-intensity focused ultrasound (HIFU). We also envision that this investigation would encourage the inclusion of nonlinear effects in the realm of computer-generated holography, allowing for the creation of specific HIFU fields to improve the efficacy and precision of therapeutic procedures.

References

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