Characterization of a Multi-Element Clinical HIFU System Using Acoustic Holography and Nonlinear Modeling

High-intensity focused ultrasound (HIFU) is a treatment modality that relies on the delivery of acoustic energy to remote tissue sites to induce thermal and/or mechanical tissue ablation. To ensure the safety and efficacy of this medical technology, standard approaches are needed for accurately characterizing the acoustic pressures generated by clinical ultrasound sources under operating conditions. Characterization of HIFU fields is complicated by nonlinear wave propagation and the complexity of phased-array transducers. Previous work has described aspects of an approach that combines measurements and modeling, and here we demonstrate this approach for a clinical phased-array transducer. First, lowamplitude hydrophone measurements were performed in water over a scan plane between the array and the focus. Second, these measurements were used to holographically reconstruct the surface vibrations of the transducer and to set a boundary condition for a 3-D acoustic propagation model. Finally, nonlinear simulations of the acoustic field were carried out over a range of source power levels. Simulation results were compared with pressure waveforms measured directly by hydrophone at both low and high power levels, demonstrating that details of the acoustic field, including shock formation, are quantitatively predicted.

Mach-Zehnder interferometry method for acoustic shock wave measurements in air and broadband calibration of microphones

A Mach-Zehnder interferometer is used to measure spherically diverging N-waves in homogeneous air. An electrical spark source is used to generate high-amplitude (1800 Pa at 15 cm from the source) and short duration (50 microseconds) N-waves. Pressure waveforms are reconstructed from optical phase signals using an Abel-type inversion. It is shown that the interferometric method allows one to reach 0.4 microsecond of time resolution, which is 6 times better than the time resolution of a 1/8-in. condenser microphone (2.5 microseconds). Numerical modeling is used to validate the waveform reconstruction method. The waveform reconstruction method provides an error of less than 2% with respect to amplitude in the given experimental conditions. Optical measurement is used as a reference to calibrate a 1/8-in. condenser microphone. The frequency response function of the microphone is obtained by comparing the spectra of the waveforms resulting from optical and acoustical measurements. The optically measured pressure waveforms filtered with the microphone frequency response are in good agreement with the microphone output voltage. Therefore, an optical measurement method based on the Mach-Zehnder interferometer is a reliable tool to accurately characterize evolution of weak shock waves in air and to calibrate broadband acoustical microphones.

Statistics of peak overpressure and shock steepness for linear and nonlinear N-wave propagation in a kinematic turbulence

Linear and nonlinear propagation of high amplitude acoustic pulses through a turbulent layer in air is investigated using a two-dimensional KZK-type (Khokhlov–Zabolotskaya–Kuznetsov) equation. Initial waves are symmetrical N-waves with shock fronts of finite width. A modified von Karman spectrum model is used to generate random wind velocity fluctuations associated with the turbulence. Physical parameters in simulations correspond to previous laboratory scale experiments where N-waves with 1.4 cm wavelength propagated through a turbulence layer with the outer scale of about 16 cm. Mean value and standard deviation of peak overpressure and shock steepness, as well as cumulative probabilities to observe amplified peak overpressure and shock steepness, are analyzed. Nonlinear propagation effects are shown to enhance pressure level in random foci for moderate initial amplitudes of N-waves thus increasing the probability to observe highly peaked waveforms. Saturation of the pressure level is observed for stronger nonlinear effects. It is shown that in the linear propagation regime, the turbulence mainly leads to the smearing of shock fronts, thus decreasing the probability to observe high values of steepness, whereas nonlinear effects dramatically increase the probability to observe steep shocks