Modeling the nonlinear interaction of ultrasound and stable cavitation gas bubbles in liquids

The propagation of ultrasound in a liquid in which a population of tiny nuclei of gas exists, due to the presence of impurities in the liquid or crevices on solid surfaces in contact with the liquid, can lead to the generation of oscillating gas bubbles (cavitation bubbles) when the amplitude of the wave is over a value that depends on the liquid (cavitation threshold). These bubbles induce dispersion effects on the sound speed and attenuation. In addition, the compressibility and nonlinear parameter of the medium can become very high. Cavitation is used in a wide range of industrial processes (cleaning, mixing, sonochemistry…). Inertial cavitation is characterized by the generation of unstable oscillating bubbles that grow and collapse. These bubbles can generate emission of light under particular circumstances. When the effect of ultrasound is not violent, these bubbles oscillate nonlinearly around their equilibrium size without collapsing during many acoustic cycles. A nonlinear interaction that involves the bubbles oscillations and the ultrasonic wave exists. The modeling of this stable cavitation process is the subject of this paper.

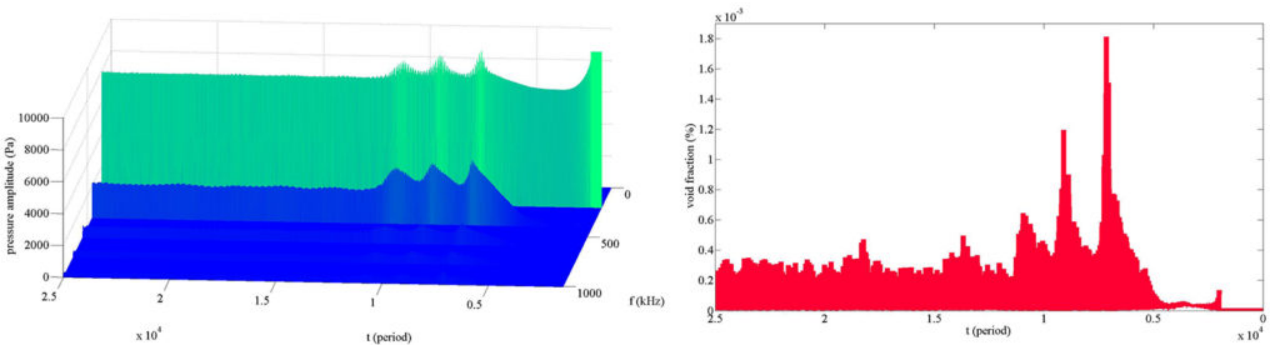

Fig. 1.

We developed a numerical model and conducted a study by considering a population of air nuclei uniformly distributed in water in a two-dimensional resonant cavity in which a standing ultrasonic field is established at the frequency of 200 kHz. The generation of bubbles relies on a nonlinear law that relates the bubble density in the liquid to the negative values of acoustic pressure and on a threshold-based mechanism. The model solves a nonlinear system of two coupled differential equations that considers dissipation and dispersion due to the bubbles. This coupling assumes that both correlated fields, ultrasound and bubble oscillations, become nonlinear during their interaction. The model predicts the distribution of cavitation bubbles in the liquid and shows their effects on the ultrasonic field.

For amplitudes below the cavitation threshold, the nuclei medium remains intact and the acoustic field remains linear at the fundamental frequency (200 kHz). Above the cavitation threshold, bigger bubbles (radius of 4.5 um) are generated and form a cloud in the area of maximal pressure amplitude. The acoustic properties of the medium are changed. The cavity is no longer resonant. After several thousands of periods, the region of new bubbles is reduced in space and is shifted towards the source. The acoustic field is hugely altered. The wave is attenuated and higher harmonics appear: 400 kHz, 600 kHz, 800 kHz, and 1 MHz, showing the nonlinear effect of the stable cavitation bubbles on ultrasound.

The ultrasound spectrogram and the evolution of void fraction in the liquid at a specific point, displayed in the Figure 1, show four successive phases. 1) A linear standing wave at 200 kHz is formed in the liquid with nuclei. 2) New large bubbles are created, they enhance the nonlinearity of the medium, and the acoustic energy is distributed from the fundamental over harmonic frequencies. 3) Pressure and bubble density fluctuate, giving rise to a medium with fluctuating nonlinearity and to variations of pressure harmonic amplitudes. 4) A strong nonlinear standing wave is established in the liquid with a quasi-stable density of large bubbles and quasi-constant harmonic amplitudes.

Results show that the energy transfer from the fundamental to higher harmonics is linked to the growth of new bubble density (growth of void fraction) in relation to the acoustic signal. They contribute to understand the formation of cavitation structures observed in experimental works. Three-dimensional simulations at higher amplitudes for higher threshold values are now required.

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