IL-3: HIFU Cavitation in Pulsed and Continuous Ultrasound Fields

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A comparative study of cavitation generated by the high intensity focused ultrasound fields (HIFU) in chopped (pulsed) and continuous ultrasound fields have been undertaken. The detailed description of the experimental set-up is given elsewhere (Dezhkunov et.al., 2011, 2000). The stainless steel cylinder of 10 cm in diameter and 16 cm in height was used as an experimental chamber. The focusing piezoceramic transducer of 65 mm in diameter with a resonance frequency of 720 kHz was mounted at the cell bottom. The hydrophone was placed in the chamber in such a way that its spherical sensitive piezoceramic unit (the diameter of 2 mm and the side thickness of 0.25 mm) was at a distance of 25 mm above the centre of the transducer's focal point. Its output (after amplification) is indicated below as H. The central region of the chamber was viewed through a light guide by a photomultiplier. Intensity of the sonoluminescence (SL) and of the hydrophone output were registered by the HP 54601 multichannel memory oscilloscope in the peak mode display regime. In investigations of the influence of pulse period T on SL intensity the value of T was decreased starting from T=2000 ms. The pulse duration τ was changed by increasing τ from 0.1 ms. The reason for changing T and τ in this manner was to decrease, as much as possible, the influence of the previous experiment on the results of the subsequent experiment.

The use of chopped ultrasound permits strongly decrease the rate of cavitation zone development and increase the time delay between the generator switching on and the cavitation appearance. By decreasing ultrasound pulse duration and increasing pulse period we were able to increase this time period up to 10 minutes.

It has been shown that cavitation zone passes through different stages of evolution with either increasing pulse duration t, decreasing pulse period T or increasing driving voltage U. Sonoluminescence (SL) is absent at the first stage, ultrasound absorbance at this stage is not increased in respect to conditions below cavitation threshold. The second stage corresponds to the onset of sonoluminescence and the smooth increase of its intensity. In the third stage, the SL intensity L increases in a sudden manner, what manifests itself through a considerable increase of slopes of the L dependencies on the above parameters (t, T, U) and is accompanied by the synchronous strong increase of the ultrasound absorption in the cavitation zone. Upon further increasing t, decreasing T or increasing U, the SL intensity reaches a maximum value and then decreases while ultrasound absorption decreases smoothly. From the above results two thresholds of cavitation zone development can be distinguished: the first one is related to the SL appearance and the second - to the sudden increase of the SL intensity, possibly due to an avalanche-like multiplication of cavitation bubbles.

Both the first and the second thresholds are increased as US pulse duration is decreased or pulse period is increased, i.e. as inverse pulse duty ratio N of the pulses is increased. Cavitation noise spectra are changed significantly with the stages of the cavitation zone development. This is indicative that the different regimes of sonification could be identified by spectral analysis of the acoustic emission from the cavitation zone. It should be noted that it is difficult to distinguish stages of cavitation zone development in a continuous ultrasound field.

Decrease of the cavitation activity after achieving L_{max} (i.e. at high bubble volume concentration) can be induced by the reasons discussed by Dezhkunov et.al., (2000, 1986), Leighton (1995). These are bubbles interactions, clustering and screening action of the cavitation field. Thus, with increasing in the density of bubbles, the SL intensity experiences the influence of two competing factors: increase of the number of cavitation events (collapses) per unit time, on one hand, and the decrease of the efficiency of concentrating the energy by bubbles upon collapse, on the other hand.

SL intensity maximum L on L(t) and L(T) dependencies is shifted to lower t and higher T respectively with increasing the ultrasound intensity. In conditions corresponding to maximal cavitation activity SL intensity achieves maximal value at the beginning of the ultrasound pulse and then stays more or less stable. In oversaturation conditions after achieving maximal value it decreases rather quickly with time. For low bubble volume concentrations SL intensity is increased with time during pulse of ultrasound.

The influence of the low frequency (LF) field on the HIFU cavitation strongly depends on both intensities of LF and high frequency (HF) fields and on pulse parameters of the HF field. In many conditions the cavitation activity estimated by the SL intensity induced by the joint action of both the HF and LF fields is up to two orders greater than a simple sum of the effects produced separately by the fields. The strong increase of the HIFU cavitation activity is observed also when HF and LF fields pulses are separated with a time delay Δt, or if one uses preliminary sonification of the liquid by the LF field. From this one may conclude that one of the mechanisms of the cavitation activity enhancenment in interacting fields of highly different frequencies is the generation of new cavitation nuclei on collapse of the cavitation bubbles initiated by the LF field. These new nuclei contain much less air than the initial bubbles from which these nuclei have been formed. Therefore, they are likely to collapse in the HF field at a higher rate than the bubbles grown from the nuclei stably existing in the liquid. Thus, owing to this mechanism both the number of cavitation bubbles and the efficiency of their collapse can increase. The last can entail an increase in the maximum pressures and temperatures attained in the vapor-gas mixture inside bubbles and, as a consequence, an increase in the SL intensity. The highest relative SL intensity increase is observed for short HF field pulses at ultrasound intensity not much higher than first SL threshold. This is in agreement with our previous results (Ciuti et.al. 2003) and results reported by Brotchie et.al (2008).

The acoustic transparencies of the cavitation zone generated by chopped and continuous ultrasound fields in water have been measured for different ultrasound intensities. It has been shown that the transparency is higher for pulsed ultrasound and it increases with the increase of the inverse pulse duty ratio N of the pulses. Pulse modulation of an acoustic field decreases the volume concentration of bubbles in the cavitation zone mainly due to the decreasing the number of big bubbles, having resonance frequency lower than the driving field frequency. As a result, the power stored during the extension phase by the collapsing bubbles increases. The intensity of the action of the bubbles on each other decreases thus providing a possibility of preserving their spherical shape down to deeper stages of collapse and increasing, correspondingly, the degree of energy concentration during the collapse with a simultaneous increase of the intensity of the effects produced by the collapsing bubbles. Bubbles clustering in chopped ultrasound field. This explains the experimentally observed increase of the sonoluminescence intensity and of the high-frequency components of the cavitation noise spectrum in chopped ultrasound fields. Moreover, a decrease of the total bubble concentration in the path of the acoustic wave decreases the screening action that limits, in many cases, the ultrasound intensity attained within a liquid volume.

Conclusion: pulse modulation of the ultrasound field is an effective tool for controlling the dynamics of cavitation zone development, transient cavitation thresholds and efficiency of acoustic energy transformation into shock waves inside and outside bubbles.

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