Acoustic Cavitation Excited by Periodic Sequence of Tone Bursts

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Introduction

Development of cavitation in liquids takes a finite time. This process can be arbitrarily divided on several stages [1]. At a first step a cloud of cavitative bubbles is produced during 10-20 periods of ultrasound wave [1, 2]. Time of bubbles cloud formation at 500-kHz excitation was clearly detected in early work of Sirotuk [3] by means of high-speed photo-registration. At the second stage the oscillating bubbles increase in size and collapse, producing new small bubbles that in turn can expand or dissolve in liquid. As a result, some distribution of bubbles is reached. The oscillating in the ultrasound field bubbles can interact which other and produce a complex pattern of bubble distribution in the space near the source of radiation [4]. The bubbles modify the density and compressibility of liquid that results in changing of the acoustic impedance of liquid and condition of sound radiation [5, 6]. As a result of these complex and interfacing processes the steady state cavitation field is produced. The duration of this process depends on sound field parameters, liquid characteristics and external conditions. A study of cavitation development is of principal importance, for example, in sonochemistry when high-speed reactions are initiated [2]. The specific aim of our work was to define a time of steady state cavitation development at different conditions of ultrasonic excitation.

Materials and Methods

Experimental Setup

A diagram of the experimental setup is shown in Fig.1. Industrial generator *(1)* was used to power supply of magnetostrictive transducer with resonance frequency of 18 kHz *(2)*. A face surface of the titanium radiator *(3)* attached to the transducer was submerged into the liquid filled the cuvette with dimensions 63x63x400 mm *(4)*. Diameter of radiator 60 mm was only 3 mm smaller the size of cuvette to prevent air capture from liquid surface. We used boiled water and transformer oil for our investigations. The pressure field was detected by the 7-mm spherical piezoelectric hydrophone with resonance frequency of 230 kHz. Measurements were performed as inside of cavitation cloud near the surface of radiator as in far field, outside it. The hydrophone size was small compared to acoustic wavelength at fundamental frequency 18 kHz (λ=8.3 cm) and it did not disturb the distribution of pressure field. On the other hand it allowed to measure of average response on several bubbles collapses near its surface. The hydrophone signal was digitized with a digital storage oscilloscope Tektronix 720A. Oscilloscope permitted recording and storage of the four realizations with 50000 samples each. The acquired with oscilloscope data were transmitted to computer connected via GPIB interface.

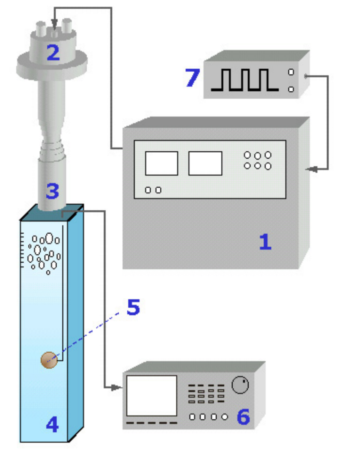

Fig. 1: Experimental setup. (1) ultrasonic generator, **(2)** magnetostrictive transducer, **(3)** titanium vibrator, **(4)** cuvette filled with liquid, **(5)** piezoelectric hydrophone, **(6)** digital oscilloscope, **(7)** pulse modulator.

Measurement Procedure

At the first step we recorded 0.1-sec signal realization just after the generator was turned on. These data corresponded to the process of cavitation development. The data corresponding to a steady state of cavitation were acquired after 5÷7 sec after beginning of ultrasound radiation. We noted visually that signal structure of the hydrophone did not change after this time therefore it was considered that the stable cavitation was developed. At pulsed regime the set of tone bursts of 0.5 duration with 4 ÷ 8 sec repetition rate was employed for cavitation excitation. The oscilloscope was synchronized with pulse generator and data can be acquired after beginning of a chosen pulse. Variation of a time interval between pulses allowed study of cavitation development with different initial gas bubble concentration.

Data Processing

The wave profiles detected by hydrophone at consequent points of time after beginning of sound radiation have evident tendency to the some stationary waveform. At the same time the wave profiles are significantly distorted with shock waves producing by collapsing bubbles therefore it was difficult to use them directly for study of cavitation field development. We proposed to employ the temporal behavior of cavitation noise spectrum for the evaluation of specific time of cavitation evolution. For this purpose acquired realization of the hydrophone signal was split on equal intervals of 50 T duration (T is the period of radiator vibrations). The spectrum was calculated for each of these intervals with use of Fast Fourier Transform. Temporal dependencies of harmonic amplitudes were analyzed.

Results

Spectra specific to cavitation noise were obtained. Each spectrum contained the pronounced harmonics (2nd, 3rd etc.) of the fundamental frequency, subharmonic and multiple frequencies, high frequency noise with approximately uniform amplitude up to several MHz. The temporal harmonic amplitudes behavior in water after the first switching on US generator is showed in Fig.2 (a-b).. The cross marks corresponding amplitude values for a steady state cavitation after 5-second interval of radiator vibration. Amplitude of the fundamental harmonic is a maximum at the beginning of cavitation process and slowly decreases with time. The amplitude decreasing is more pronounced when the measurements were performed outside cavitation field, where only single bubbles can appeared. Amplitude of vibration of radiator itself was stabilized for 80 T, which is small compared to the characteristic times of the process. Amplitudes of high order harmonics increase for several

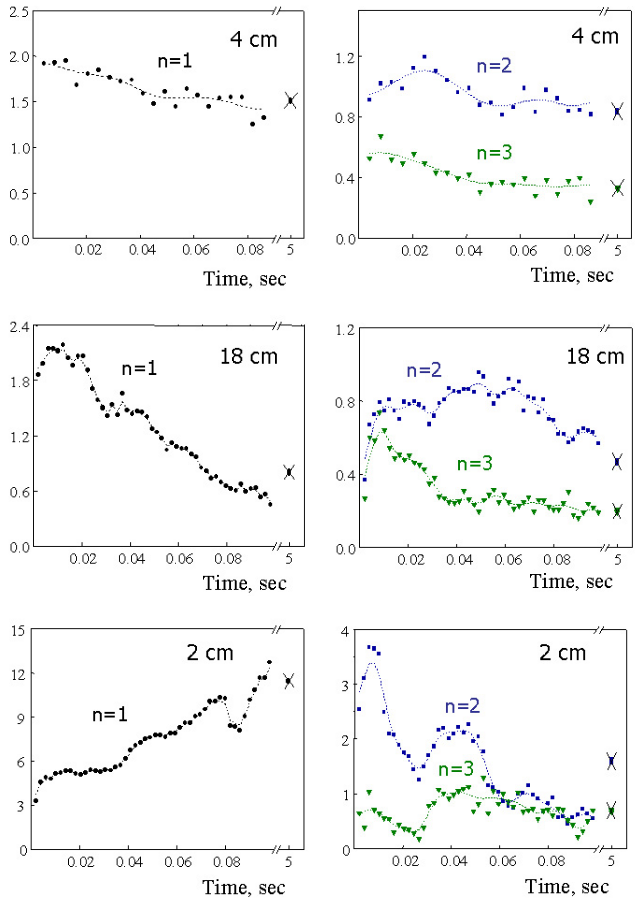

Fig. 2: Temporal dependence of the fundamental harmonic (n = 1), the 2^nd^ (n = 2) and the 3^rd^ (n = 3) harmonic amplitudes.
(a) in water inside a cloud of cavitative bubbles (4cm from radiator surface); **(b)** outside it (18 cm from radiator surface) ; **(c)** in transformer inside a cloud of cavitative bubbles (2 cm from radiator surface)

hundred of sound periods and then they are reduced slowly approaching steady state values. Time of cavitation development in undisturbed water can be estimated as 40÷50 ms, or $2000 \div 2500T$. Near vibrator surface, inside cavitation cloud, amplitudes of harmonics were varied in the range 40÷60%, whereas the corresponding harmonics variations in far field were essentially greater and reached 300÷400%.

Time of cavitation development was reduced when the consequent radiation of ultrasound pulses was employed. It was shown, for example, that when the interval between consequent pulses was 4 sec time of a stationary cavitation development was reduced to 20 ms from pulse to pulse during $3 \div 4$ pulses, and beginning from fifth or sixth pulses this time was stabilized at 15÷18 ms level. Amplitudes of harmonics were reduced for $40 \div 60\%$ compared to the initial values obtained at the first switching on. Specific values were varied with duration, number and repetition rate of ultrasound pulses.

Theoretical Model

The complete system of the equations describing the cavitation development should consist as a minimum of three interdependent blocks of the equations [7]. The block includes equations connected with propagation of sound wave in bubbly medium. The equations are related to the scattering and the processes of bubbles coalescence and splitting. And the block describes dynamics of a single bubble. Each block of the equations can be characterized by the set of the characteristic times. The time of collapse of a single bubble by means modified Gilmore– Akulichev equation was considered in our work:

$$R\left(1+\gamma R-\frac{U}{C}\right)\frac{dU}{dt}+\frac{3}{2}\left(1+\frac{4}{3}\gamma R-\frac{U}{3C}\right)U^2-$$

$$-\left(1+\frac{U}{C}\right)H-\frac{U}{C}\left(1-\frac{U}{C}\right)R\frac{dH}{dR}=0$$

Where R is the bubble radius, $U=dR/dt$, H is the difference in enthalpy between the bubble wall and infinity, C *is* the speed of sound, that can be expressed as a function of enthalpy. The bubble interaction is described by the phenomenological parameter $\gamma=\pi a^2 n_0$, where n_0 is the bubble concentration in the cavitation cloud, a is the radius of the cloud. For computer simulations we proposed that parameter depends on time as $\gamma = \gamma_0 \arctan (kt/t_0)$, where k and t_0 are the parameters of the problem. Computer simulations of bubble dynamics showed that with increasing of parameter γ time of collapse of a single bubble is reduced twice or more, and the bubble radius increasing is also reduce.

Conclusions and Discussion

In the process of cavitation development the relations between spectrum components is changed with a tendency to the spectrum of a stable state cavitation. It was found that time of steady state cavitation development was about 40-50 ms for our experimental conditions. Measured value was of several orders of magnitude greater then time of cavitation cloud formation. Time of steady state cavitation development was twice reduced when periodical sequence of US pulses was employed for cavitation excitation. To interpret the received results it is possible to state some assumptions. Closed to the radiator surface the movement of particles of medium is directly connected to movement of the radiator surface. Therefore near to the radiator the field is established quickly enough. The amplitude of harmonics far from a radiator depends on radiation from whole cavitation region. During development of a cavitation the acoustic impedance of medium decreases as simultaneously decrease density and speed of a sound. Therefore amplitudes of harmonics at the beginning grow and then stabilize thus follow to dynamics of bubble number. Proposed theoretical model shows that initial gas bubble concentration plays significant Such explanation of the phenomenon, however, will not absolutely be coordinated to results received in transformer oil Fig.2 (c). In this connection it is planned to lead additional theoretical and experimental investigations.

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