TEMPORAL EVOLUTION OF CAVITATION FIELD GENERATED BY PULSE-PERIODIC ULTRASOUND

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Development of acoustic cavitation in liquids was studied experimentally and theoretically. The measurements were performed in water and transformer oil. The cavitation was excited by continuos and pulse ultrasound (US) oscillations at 18 kHz. US oscillations were switched on for approximately 0.5 sec. every 4-8 seconds. Acoustic pressure time dependencies were measured for various distances from the transducer during first 0.1 s after cavitation beginning. The acquired pressure profiles were split by time, 50 periods of US wave each, and amplitudes of fundamental frequency, harmonics and subharmonics were calculated for the each piece. It was shown that cavitation development time decreases after second US pulse. It also substantially depends on number of exposures, their length and repeat frequency. A computer simulation experiment on bubble dynamics in US wave (including bubble interactions) was performed. Modeling results had shown that bubble shrinking time depends on interaction parameter, both on its value and alteration character, and decreases with the increase of this parameter's initial value. Good agreement with experimental data was demonstrated.

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 bubbles modify the density and compressibility of liquid that results in changing of the acoustic impedance of liquid and condition of sound radiation [4,5]. 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 set up. A detail description of the experimental set up can be found in [5]. Magnetostrictive transducer with 18 kHz resonance frequency was driven by a powerful industrial generator. Rectangular pulses with various length and period for transducer excitation were generated by a special circuit. Magnetostrictive transducer was equipped with a dumb-bell titan concentrator. The surface of the titan concentrator was immersed in an organic glass tray filled with studying liquid. A 7-mm spherical hydrophone with 230 kHz resonance frequency was used for acoustic pressure detection. The hydrophone signal was detected with a Tektronix TDS 520A oscilloscope. LabView software package was used to transfer the acquired data to a PC.

Method. The hydrophone was placed at a fixed distance (40 or 150 mm) from the concentrator surface near the tray center. US generator was driven by 0.35 sec rectangular impulses with 4-sec repetition cycle. Data were acquired during 0.1 sec after beginning of the 1-st, 3-d, 6-th and 9-th pulses. The procedure of measurement allowed calculating of 14 harmonics of the main frequency correctly.

After US generator turning on the bubble cloud was appeared near the oscillator surface, and cavitation noise can be heard. Cavitation region was approximately 10 cm long. Outside this region only single bubbles can be found. The hydrophone was placed as inside cavitation region (4 cm from oscillator) and outside it (15 cm).

Data processing. The acquired pressure profiles were very complex and strong fluctuating due to bubble collapse and chaotic bubble oscillations, and it was difficult to determine bubble's evolution characteristics directly from the temporal evolution of the wave profile. It was preferable to use some averaged values that could describe slow (compared to oscillation period) wave evolution. On the other hand the gap taken for averaging should be smaller than stabilization time (approx. 50 periods). For this purpose average harmonics amplitudes were used (averaged over an finite length realization). Spectral analysis is accomplished by FFT procedure built into MATLAB software package. Data file was split into pieces with 2^n points in each piece (in this paper n=10), FFT was performed and a spectrum of the certain piece is received. Then harmonics, subharmonic and its multiple frequencies amplitudes are calculated. The harmonic evolution matrixes were received as a result.

Results. Noise components were changed during cavitation development and tended to steady cavitation spectrum. Figures (1a,1b) show evolution of fundamental frequency and second harmonic for the first and the sixth US pulses. Measurements were performed in boiled settled water.

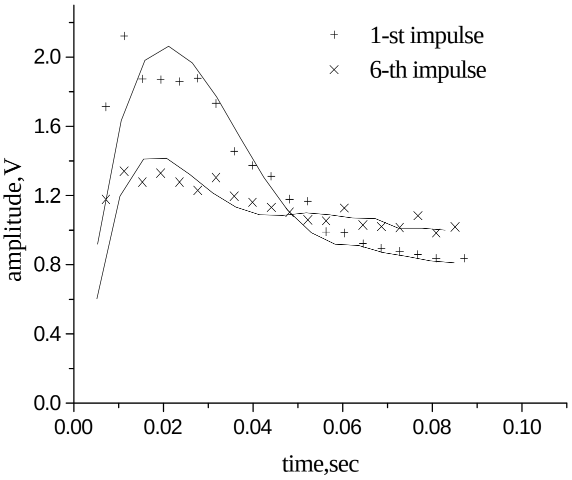

Figure 1a. Time dependency of fundamental frequency amplitude during the 1-st and the 6-th excitation pulse.

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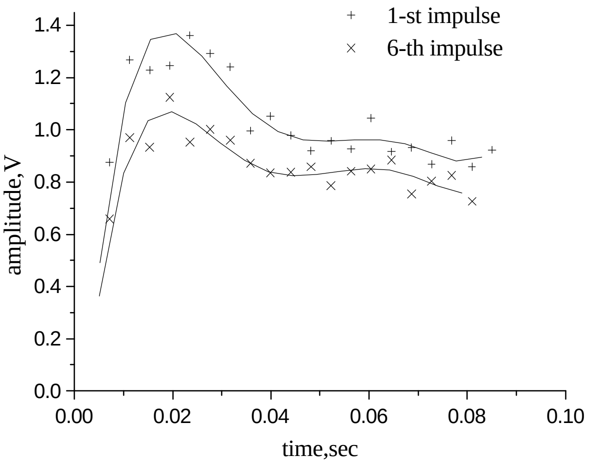

Figure 1b. Time dependency of the second harmonic amplitude during the 1-st and the 6-th excitation pulse.

The figures show that cavitation development can be divided into two stages. At the initial stage the harmonic amplitudes grow up and reach their maximum. It happens during 10-15 ms, that corresponds to 200-300 oscillation periods. At the second stage harmonic amplitudes were decreased and tended to stabilization. The value of amplitude harmonic's maximum is decreases from impulse to post and have evident tendency to the some stationary level, beginning roughly from 10^{th} pulse. Note, that value of steady-state maximum depends of pulses duration and period its repetition. Stabilization time of harmonics amplitudes also decreases with growth number of switches US hesitations. For chosen pulse excitation mode stabilization time decreases practically in 2 times for 6^{th} switch in comparison with radiation in unexcited liquid. Maximal amplitude of fundamental frequency and stabilization time, for the 1^{st} impulse, is 2.1 V and 60-80 ms respectively. For the 6^{th} impulse amplitude decreases down to 70%, and stabilization time to 40-50 ms. Second harmonic values are as follows: 1.4 V and 40-50 ms for the 1^{st} impulse and 70% and 30-40 ms for the 6^{th}. The same tendency can be obtained for higher harmonics and subharmonic.

Theoretical model

The process of cavitation development is based on equations describing dynamics of a single bubble. Modified Kirkwood – Bette equation was used in our study:

$$R\left(1+g\,R-\frac{U}{C}\right)\frac{dU}{dt}+\frac{3}{2}\left(1+\frac{4}{3}g\,R-\frac{U}{3C}\right)U^{2}-\left(1+\frac{U}{C}\right)H-\frac{U}{C}\left(1-\frac{U}{C}\right)R\frac{dH}{dR}=0\,.$$

Here R is the bubble radius, $U(t)=dR/dt$, $H=\int\limits_{P_\infty}^{P(R)}\frac{dp}{r}$ is the difference in enthalpy between the bubble wall and infinity, $P_\infty = P_0 + P(t)$. Condition equation was used in a form : $p = A\left(\frac{r}{r_0}\right)^{n} - B$, where A, B, n are constants (for water A=3001 bar, B=3000 bar, n=7) [3] . Speed of sound can be expressed as a function of enthalpy: $C=\sqrt{C_0^2+(n-1)H}$. The bubble interaction is described by the phenomenological parameter $g = pa^2 n_0$, 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 $g = pa^2 n_0$ depends on time as: $g = g_0 arctg(kt/T_0)$, where k is the parameter characterizing the quickness of the bubbles concentration growth, and T_0 is the period of ultrasound wave. Runge-Kutta method of the 4-th order built in MATLAB software was employed for the numerical solution of Kirkwood – Bette equation. Figures (2a,2b) show results for following parameters: **:** R_0-initial radius-1 mkm ; P-amplitude of sound pressure-10 bar; f- frequency-18 kHz ; ê=1,2; γ_0= 0.015 R_0. Figures show, that time of bubbles collapse depend on value and way of development interaction parameter.

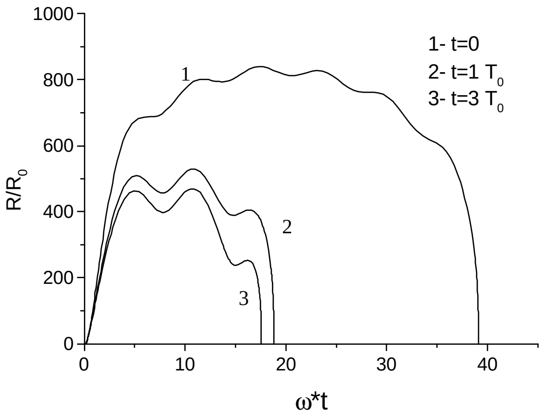

Figure 2a. The temporal dependence of bubble radius at γ_0=0.015 R_0, k=1 for vary initial times.

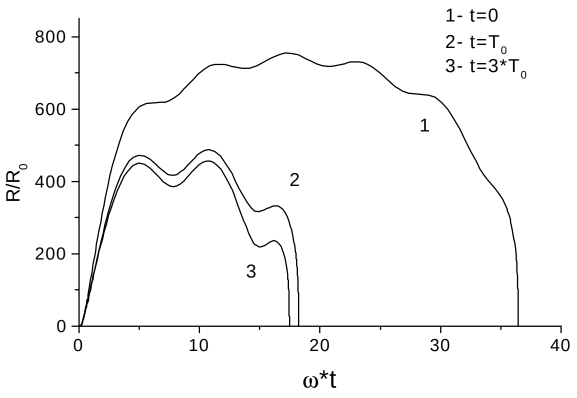

Figure 2b. . Time dependency of bubble radius at γ_0=0.05 R_0, k=2 for vary initial times.

Curve 1 (initial value γ=0) [2a] shows the growth of bubble in 800 times. Time of collapse of a single bubble at these conditions is about 6 periods of US wave. The curve2 (initial value $g = g_0 arctg(k)$**)** shows the growth of bubble in 500 times. Time of collapse of a single bubble in this conditions is decreased almost 2 times in comparison with first case. The curve 3 appropriate initial value $g = g_0 arctg(3k)$**.** In this case γ depends on time low and approaches to stationary value. Figure (2b) show results at k=2.

Conclusion

Method for study of the cavitation development is proposed. It is based on analysis of temporal evolution of a cavitation noise spectrum. It was found that time of steady state cavitation development was about 60-80 ms for excitation US on unexcited liquid and decreases to 40-50 ms with increases number of switches. Computer simulation experiment on bubble dynamics in US wave (including bubble interactions) show, that time of bubble collapse decreases by aspiration γ to stationary value.

REFERENCES

1. L.D.Rozenberg. Cavitation fields. In “Power Ultrasound Fields”,Moscow, Nauka, 1968, pp.221-266
2. R. Mettin, S. Luter, C.-D. Ohl, W. Lauterborn, Ultrasonics Sonochemistry. 1999, No. 6. pp. 25-31.
3. M.G. Sirotuk, Experimental investigation of ultrasound cavitation. In “Power Ultrasound Fields” (edited by L.D. Rozenberg), Moscow, Nauka, 1968, pp. 167-235.
4. V.G.Andreev, N.B.Brandt, O.V.Rudenko. Nonlinear radiation of a piston vibrating with high amplitude. Proc. of 5-th International Congress on Sound and Vibration, v.4, Adelaide, 1997, 1815-1820
5. V.G.Andreev, G.A. Romanenko. Experimental study of acoustic wave spectrum evolution in caviting liquid. Moscow State University Bulletin, 2001, v.41, No.1, 60-63.