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Analysis of the mechanism of generation of the continuous cavitation noise component

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It is demonstrated that a disturbance of periodicity of pulsations of cavitation bubbles at different points of an ultrasonic field may be one of the mechanisms of generation of the continuous component in the cavitation noise spectrum. The contribution of this factor increases with an increase in the degree of aperiodicity of perturbations induced by bubbles and is not related explicitly to the intensity of shock waves generated when bubbles collapse. Experimental data verifying this conclusion are presented.

Keywords: cavitation, bubble collapse, white noise, sonoluminescence.

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Cavitation is the phenomenon of formation, pulsations, and collapse of gas microbubbles in liquid under the influence of varying pressure [1]. A complex acoustic signal (cavitation noise, CN) is generated in the course of pulsations and collapse in the cavitation region [1,2]. It was noted in a number of studies (see, e.g., [3–7]) that cavitation noise may be used to detect and examine cavitation via spectral CN analysis. It is believed that the mechanism of generation of the continuous CN spectrum component involves cavitation bubble collapse (i.e., transient cavitation). This hypothesis is grounded in the fact that a shock wave, which may be approximated roughly by a delta function [6,7], is produced upon bubble collapse. As is known, the delta function spectrum is continuous. In view of this, the continuous component of CN (CCCN) is used widely to estimate the intensity of transient cavitation [5,7,8].

In the present study, the mechanism of CCCN generation is analyzed by modeling the probable distortion (perturbations) of the initial sinusoidal ultrasonic field induced by cavitation bubbles. The following algorithm was used. In the pre-cavitation regime, the pressure in a sonic field is assumed to vary in accordance with a sinusoidal law. When cavitation commences, acoustic perturbations are superimposed onto the initial sinusoidal signal. The resulting perturbation type is chosen relying on the known regularities of dynamics of individual bubbles and the cavitation region as a whole. A digital representation of the signal formed this way is subjected to Fourier spectral analysis.

As a first approximation, let us examine the case of an individual bubble in a spherically symmetric focused ultrasonic field. This is the case investigated in experiments on single-bubble sonoluminescence (SBSL) [9,10]. A rapid bubble compression (collapse) in such a system occurs at the end of the first half (or at the start of the second half) of the half-period of ultrasonic wave compression. The process is repeated with fine periodicity in one and the same phase of each period and is accompanied by an acoustic pulse and a sonoluminescence burst that are generated simultaneously [9]. The resulting acoustic signal is shown in Fig. 1, *a*, and Fig. 1, *b* presents the result of spectral analysis of this signal. The spectrum includes fundamental frequency F_0 and harmonics nF_0. No continuous component is present.

The data reported in [9] indicate that a single-bubble system enters the regime of unsteady sonoluminescence when sonic pressure P_A rises above $1.5P_0$, where P_0 is the hydrostatic pressure. A bubble is unstable in this case and oscillates chaotically in space around the point of maximum pressure. The phase of pulsations of such a bubble varies stochastically about a certain mean position relative to the wave phase. To model the corresponding acoustic signal, shifts Δt from the mean position were set for a pulse generated by a bubble in each subsequent period of ultrasound. These shifts varied in random manner with the maximum magnitude limited to Δt^*. A stochastic nature of shift Δt was guaranteed by adding a value of Δt^* multiplied by a random number falling within the range from 0 to 1 to the chosen time moment of pulse emergence. A sequence of random numbers was generated with the use of a function [10].

Figure 2, *a* presents the spectrum of the obtained signal. It is evident that it features a fundamental frequency, harmonics, and a continuous component. Figure 2, *b* shows the dependence of the mean CCCN power on Δt^*, which specifies the degree of aperiodicity of bubble pulsations. It follows from the presented data that the magnitude of CCCN, which is established by the aperiodicity of acoustic perturbations, increases rapidly with Δt^* and may produce

Dependence of photomultiplier output signal L and continuous component H of an acoustic signal

Parameter	U, V							
	150	175	200	225	250	275	300	320
L, mV	372	410	347	272	193	146	139	137
H, mV	47.4	47.1	51.6	54.0	61.5	62.7	64.9	66.3

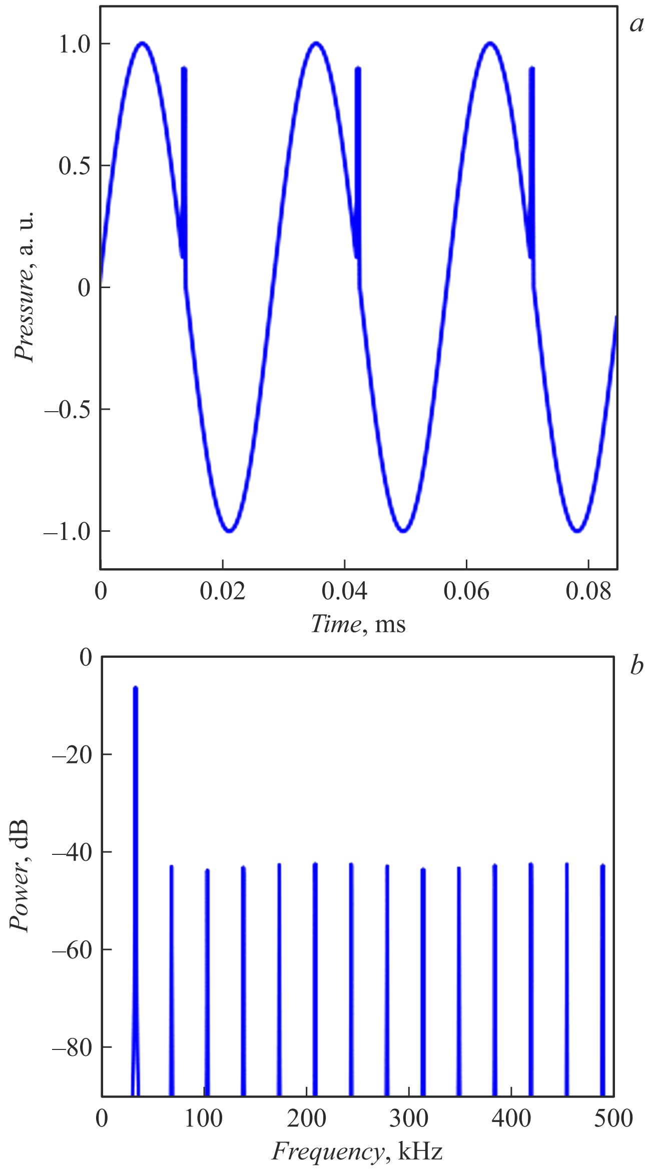

Figure 1. Acoustic signal (a) and its spectrum (b) in the case of periodic pulsed perturbation of a sinusoidal signal (SBBL). $F_0 = 35$ kHz, and the periodic pulse height is $0.9P_A$ (P_A is the acoustic pressure amplitude).

a significant (if not decisive) contribution to the resulting CCCN value.

In a multibubble cavitation region, the resulting acoustic signal in any given sufficiently small field region (point) containing a sensor is formed from perturbations produced not only by nearby bubbles, but also by those located at a considerable distance. Pulses from remote bubbles arrive at the given point with a certain delay relative to the moment

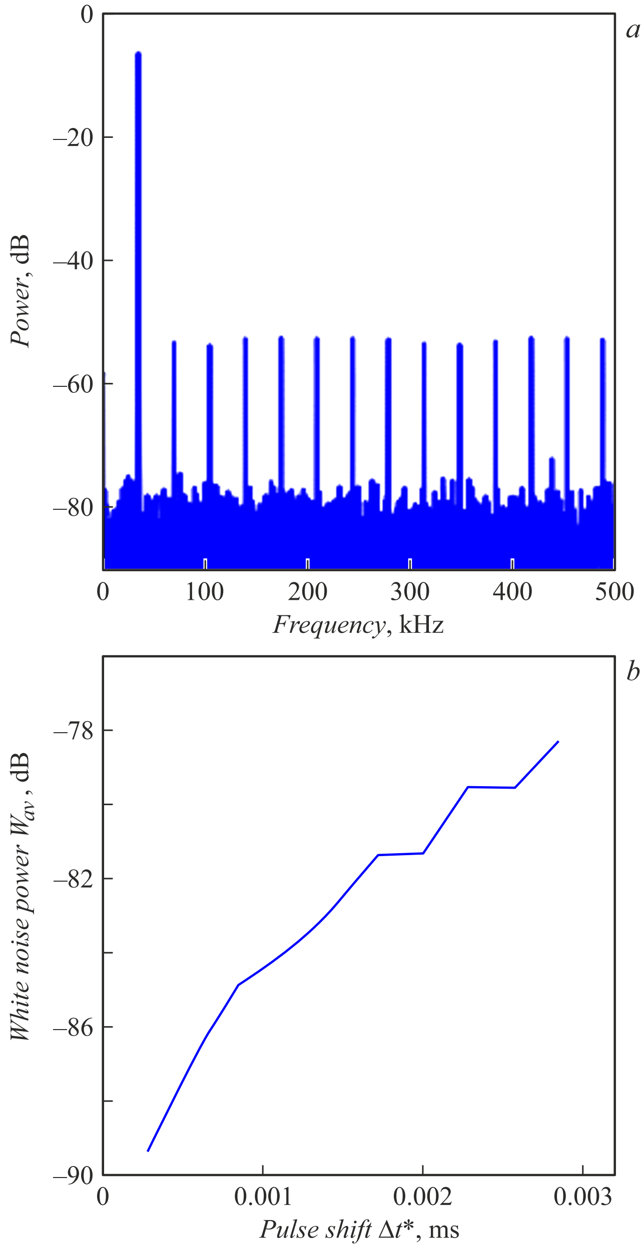

Figure 2. Spectrum of the resulting acoustic signal in the case of unsteady SBBL (a) and dependence of the mean CCCN power of this signal on Δt^* (b). $F_0 = 35$ kHz, and the pulse height is $0.3P_A$.

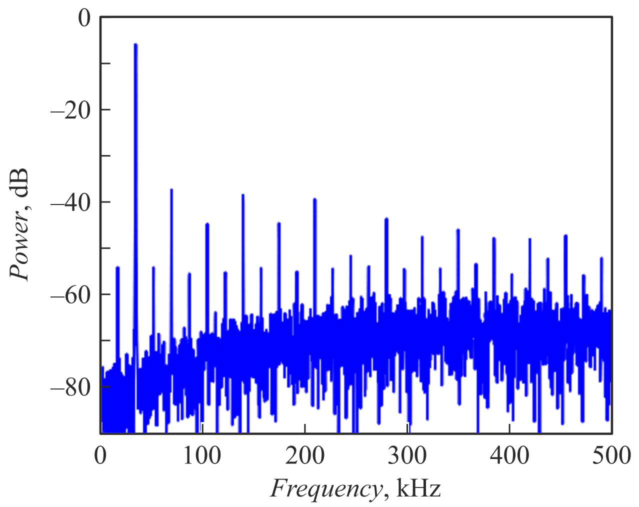

Figure 3. Spectrum of the acoustic multibubble sonoluminescence signal. $F_0 = 35$ kHz, and the aperiodic pulse height is $0.3P_A$.

of collapse. As is known [1,11,12], a cavitation region contains bubbles of different sizes, and the size distribution may vary from one period to another. The process dynamics changes in accordance with size: collapse occurs at time points positioned differently relative to the acoustic wave phase. In addition, owing to their interactions among themselves and with the field, bubbles move stochastically within the volume of liquid and disintegrate when collapsing. In view of the above, it seems rational to assume that the resulting acoustic perturbation produced by a multibubble cavitation region at a given field point cannot be strictly periodic. This perturbation was modeled in the present study as a sequence of pulses with their intensity and phase varying randomly within a certain given range of values. The resulting signal spectrum includes the fundamental frequency and the continuous component.

The size distribution of bubbles in a cavitation region has the form of a curve with a maximum [11]. The majority of bubbles (more than 50%) are grouped in a narrow size range. It is evident that bubbles from this range collapse with an insignificant delay relative to each other, forming a quasiperiodic pulse (i.e., a pulse with its phase varying chaotically about a certain position relative to the wave phase). It follows from our analysis that the spectrum of the resulting signal includes the fundamental frequency, harmonics, and a CCCN.

It has been demonstrated in [13] that a cavitation region with a sufficiently high concentration of bubbles pulsates as a whole with a frequency below F_0 (e.g., $F_0/2$). However, even then bubbles do not collapse simultaneously. Therefore, a periodic addition induced by cavitation region pulsations should have the form of periodic noise that repeats, e.g., every other period. The spectrum of this signal (Fig. 3) includes the continuous component, harmonics nF_0, subharmonic $F_0/2$, and frequencies $(2n+1)F_0/2$; i.e., it agrees completely in its composition with the experimentally measured CN spectra [4,7].

We have also verified experimentally the conclusion regarding the ambiguity of relation between the continuous component of CN and cavitation bubble collapse and shock waves produced in the process. Experiments were performed using the setup discussed in [5,8] in a pulsed focused field with a frequency of $F_0 = 720$ kHz. Photomultiplier output signal L and continuous component magnitude H were recorded at ultrasound pulse width $\tau = 5$ ms and pulse repetition period $T = 15$ ms. The results of measurement of L and H at various radiator voltages U are listed in the table. It can be seen that the sonoluminescence intensity at the given ultrasound parameters starts decreasing with increasing U at radiator voltages above $U = 175$ V, while the CCCN intensity rises; i.e., these parameters are negatively correlated.

A reduction in sonoluminescence intensity with an increase in ultrasonic oscillation intensity is observed at the fourth stage of development of a cavitation region [8], when it becomes oversaturated with bubbles. This state is characterized by intense interactions between bubbles and their disintegration into fragments at the early stage of collapse, which may enhance both the variation of bubble concentration from one period to the other and the aperiodicity of collapse. Thus, it has been demonstrated for the first time that an aperiodic nature of pulsations and collapse of bubbles in a cavitation region is a probable mechanism of generation of the continuous component in the cavitation noise spectrum. This result is important in terms of advancement of cavitation study techniques and has prospects for application in, e.g., instruments for monitoring the cavitation activity level and the cavitation regimes of ultrasonic technology processes in liquids.

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Conflict of interest

The authors declare that they have no conflict of interest.

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