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Study of cavitation noise without subharmonics

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The evolution of the cavitation noise (CN) spectra in the field of a focusing emitter with an increase in the intensity of ultrasound (US) was studied. Spectra without subharmonics $f_0/2$ were recorded for the first time, where f_0 is the frequency of the ultrasound generating cavitation,. Such a spectrum is observed in partially degassed water at a high duty cycle of ultrasonic pulses. The threshold for the appearance of sonoluminescence (SL) coincides with the threshold for the appearance of the frequency $f_0/2$ in the CR spectrum. In a pulsed field at an ultrasonic intensity much higher than the cavitation threshold, the SL intensity increases with an increase in the duty cycle of the pulses, while the intensity of the $f_0/2$ line in the CS spectrum decreases.

Keywords: sonoluminescence, subharmonics.

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Cavitation is the phenomenon of formation, pulsations, and collapse of gas microbubbles in liquid. Rayleigh was the first to analyze the collapse of microbubbles [1]. The effects observed experimentally in the process of bubble collapse are accompanied by acoustic signals (cavitation noise), chemical reactions, and light emission. This emission of light has been detected for the first time in liquids cavitated by ultrasound (US) [2] and is commonly referred to as sonoluminescence (SL). The acoustic method was developed further in the study of bubble SL in relation to the properties of emitted light [3]. While theoretical models are focused on the dynamics of individual microbubbles, experimental studies deal mostly with multibubble SL. Differences between hydrodynamic cavitation in intense shear flows [4] and acoustically induced SL, wherein bubbles generate SL in a large number of cycles in the context of cavitation „memory" [5], were noted. A complex acoustic signal (cavitation noise, CN) is generated in the course of pulsations and cavity collapse in the cavitation region. Since CN is produced by moving bubbles, many authors suggest rather reasonably [6–8] that it should contain data on the state of the cavitation region and the dynamic behavior of bubbles. Therefore, spectral analysis of CN may be an efficient technique for cavitation studies. In the fully-developed cavitation regime (i.e., with the US intensity well above the cavitation threshold), the CN spectrum includes fundamental frequency f_0 of the cavitation-inducing ultrasound field, harmonics nf_0 (n is an integer number), subharmonic $f_0/2$, frequencies $(2n+1)f_0/2$, and a continuous white noise component. The development of CN-assisted cavitation study methods is hampered by the fact that the mechanisms of generation of CN spectral components are not fully understood [8]. According to [9], the presence of subharmonic $f_0/2$ in the acoustic signal is attributable to pulsations of bubbles that are twice the resonance size. Alternative mechanisms of production of the $f_0/2$ component involve the excitation of standing waves on the surface of large bubbles [10] and pulsations of the cavitation region as a whole in the vicinity of an emitter with frequency f_0/m [11]. The authors of [12] proposed to use subharmonic $f_0/2$ to detect cavitation and estimate its intensity level.

The present study is the first to report the results of measurement of CN spectra without subharmonic $f_0/2$. It is demonstrated that a negative correlation between the intensities of this subharmonic and SL is observed in a pulsed ultrasound field with an increase in the duty cycle of pulses. A detailed description of the setup and the experimental procedure was provided in [13]. The working vessel is a stainless-steel cylinder with hollow water-cooled walls with an inner diameter of 100 mm and a height of 180 mm. A focusing piezoceramic ultrasound emitter 65 mm in diameter with a focal distance of 60 mm is mounted at the bottom of the vessel. The resonance frequency of the piezoelectric element is $f_0 = 720$ kHz. A hydrophone is introduced through the lid of the vessel and positioned in such a way that its receiving piezoceramic element 2 mm in diameter and 0.25 mm in thickness is located 20 mm beyond the focal point of the emitter.

Figure 1 presents the spectra of cavitation noise measured at an increasing US intensity, which was varied by adjusting voltage U applied to the emitter. Figures 1, a, c show the spectra in a continuous US field; the liquid is distilled water without additional degassing at a temperature of $22.0 \pm 1.5^\circ$C. Figures 1, b, d present the spectra in a pulsed field with pulse length $\tau = 2$ ms and pulse repetition period $T = 200$ ms; the liquid is distilled water at a temperature of $22.0 \pm 1.5^\circ$C degassed by boiling in accordance with

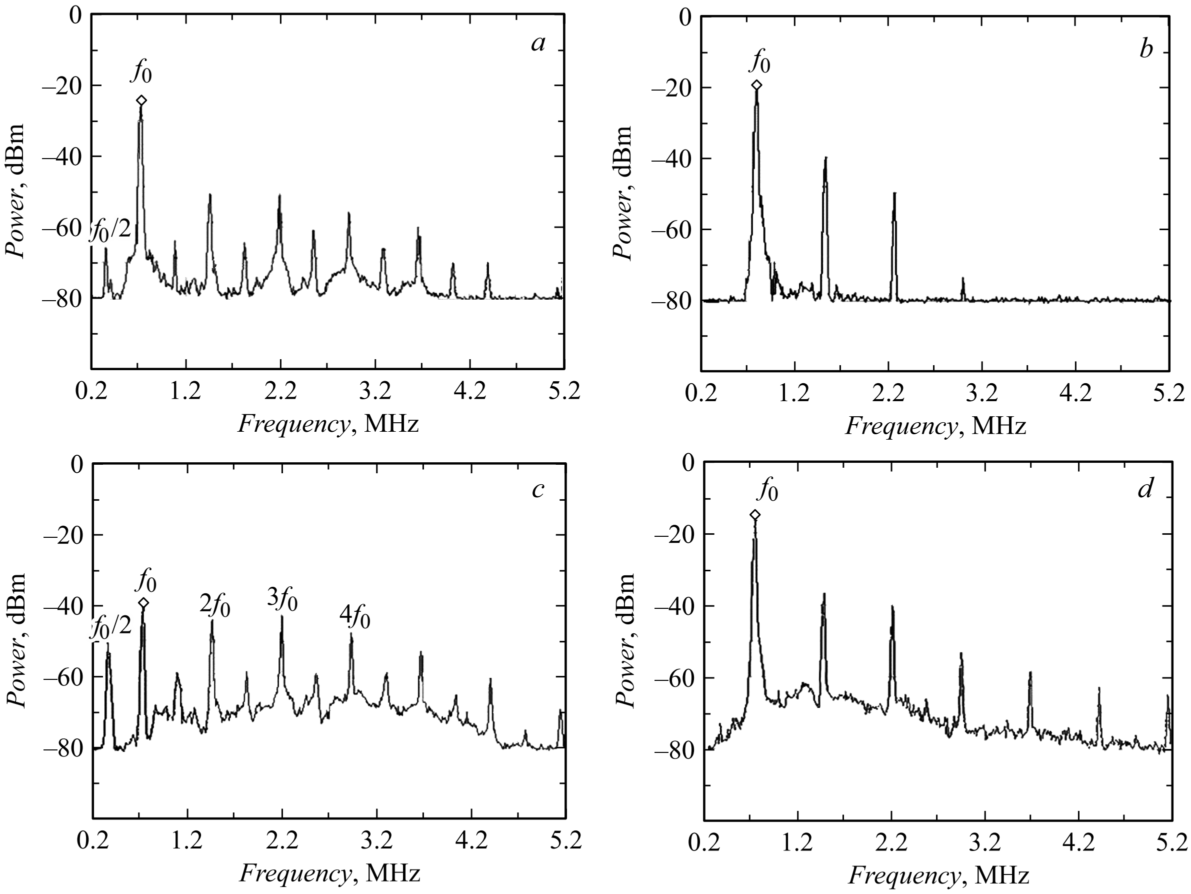

Figure 1. Evolution of CN spectra with an increase in voltage U at the emitter. U, V: a, b — 45, c — 150, and d — 175. a, c — In a continuous US field; b, d — in a pulsed field with pulse length $\tau = 2$ ms and pulse repetition period $T = 200$ ms. See text for details.

the procedure outlined in [14]. Harmonics nf_0 and subharmonic $f_0/2$ are marked in Fig. 1, c. In a continuous field, all CN spectral components (f_0, $f_0/2$, nf_0, $(2n+1)f_0/2$, and the continuous component) are present even at relatively low US intensities (Fig. 1, a). According to [15], this mode corresponds to the second stage of development of the cavitation region (the US intensity is several times higher than the SL threshold in the given conditions). As the US intensity increases ($U = 45-75$ V), all CN components except for f_0 become more intense. The SL intensity grows rapidly in this mode. It was found that the SL activation threshold in a continuous field matches (at least within the accuracy of measurements) the threshold of emergence of frequency $f_0/2$ in the CN spectrum. This agrees with the data from [16]. The f_0 intensity decreases considerably at a US intensity ($U = 150$ V) that is well above the SL threshold (Fig. 1, c). This is evidently attributable to an enhancement of US absorption in the cavitation region due to an increase in the volume density of bubbles in the path of a sound wave. Since the SL intensity also decreases in this case, it is fair to say that the volume density of bubbles increases mostly due to bubbles with above-resonance sizes. These bubbles pulsate with only minor size variations and do not produce emission, but absorb and scatter the US energy efficiently. The interaction of bubbles with each other via shock waves and Bjerknes forces is an important factor of SL intensity reduction at a high bubble density. In view of the instability of a spherical bubble shape upon collapse [17], these interactions may result in disintegration of a bubble into fragments at the early stage of collapse [18], thus reducing the efficiency of conversion and concentration of the US energy. In addition, the screening effect of the peripheral part of the cavitation region becomes more pronounced as the bubble concentration increases [18].

The spectral composition of CN in a pulsed field (Figs. 1, b, d) differs from the one examined above: frequency $f_0/2$ is lacking, and the signal level at frequencies f_0 and nf_0 is higher. A high f_0 level implies that the US energy absorption in the cavitation region in a pulsed field is less pronounced than the absorption in a continuous field.

Figure 2 presents the dependences of output photomultiplier signal L (curve *1*) and subharmonic intensity S (curve *2*) on repetition period T of pulses of the sound field. A negative correlation between L and S is observed at $T = 3-100$ ms: the SL intensity increases with T, while the subharmonic intensity decreases as the pulse repetition period grows. If we follow the hypothesis proposed in [9] and assume that the subharmonic generation in the CN

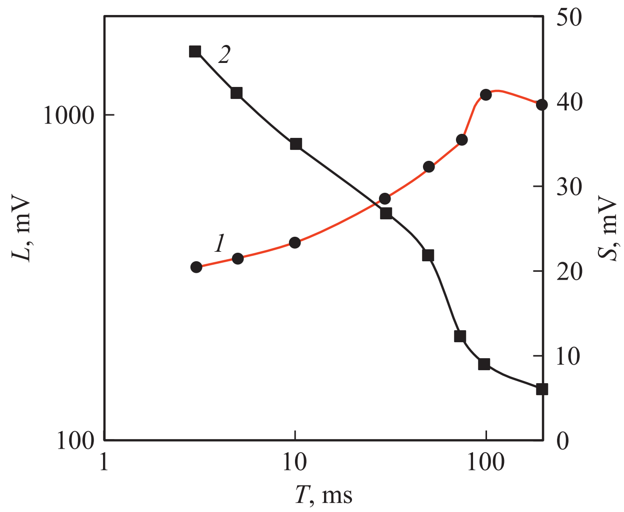

Figure 2. Dependences of SL L (*1*) and subharmonic S (*2*) intensities on US pulse repetition period T ($\tau = 2$ ms, $U = 175$ V).

spectrum is related to pulsations of large bubbles, the data presented in Fig. 2 may be explained in the following way. As duty cycle T/τ increases, time interval $T - \tau$ between consecutive pulses also grows. Cavitation nuclei produced under the influence of US grow smaller within this time interval due to the diffusion of gas from a bubble into liquid. Thus, at high T values and a constant τ, liquid relaxes to a considerable extent toward the initial state (i.e., the state unperturbed by US with the corresponding concentration and size of nuclei) by the time the next pulse arrives. As $T-\tau$ becomes shorter, the degree of relaxation of cavitation liquid properties naturally decreases. Consequently, the concentration of cavitation nuclei and their size at the start of each period will be higher than the corresponding values at the start of the preceding period. The concentration and size of bubbles in the cavitation region are thus expected to increase when T decreases at a constant τ. Therefore, the probability of formation of large bubbles (e.g., due to coalescence under the influence of Bjerknes forces [19] and rectified diffusion) should increase also, thus inducing the growth of the subharmonic intensity at lower T values (curve *2* in Fig. 2). On the other hand, the SL intensity growth at higher T values (curve *1* in Fig. 2) is attributable to an improvement of the efficiency of conversion of the US energy into other types of energy under the influence of factors that were discussed above [8].

Thus, CN spectra without subharmonic $f_0/2$ have been measured for the first time in the present study. These spectra are observed in partially degassed water at a high duty cycle of ultrasonic pulses. Therefore, this CN spectrum component cannot be used to detect cavitation in pulsed ultrasound fields. The obtained results verify the hypothesis that the subharmonic is generated by large cavitation voids with above-resonance sizes.

It is of interest to compare the results of examination of SL spectra under hydrodynamic cavitation in intense shear flows, wherein cavitation glow is normally associated with a single cycle of growth and collapse of voids, and acoustically induced SL (with bubbles continuing to produce SL over many cycles). Four different cavitation regimes were identified in the study of hydrodynamic SL in flows incident on a tilted plate (wing) at different incidence angles [20]. At low angles (2°), separate cavitation bubbles had a hemispherical shape. When the incidence angle increased to 4°, separate bubbles gave way to a continuous region in the form of a sheet attached to the leading edge of the plate. This region became unstable at angles above 7°, giving rise to clouds of cavitation bubbles. When the incidence angle became greater than 12°, the boundary layer detached from the leading wing edge, inducing the formation of voids at the core of vortex structures generated in the recirculation zone. It was found that the intensity of cavitation luminescence at the minimum incidence angle increased with velocity C of the flow perturbed by the wing and followed a power law with exponent $\alpha = 3.9{-}7.2$. A similar power-law behavior was identified for the intensity of acoustic noise produced by cavitation with exponent $\alpha = 4.8{-}5.9$ for velocity C. Measurements of the erosion rate (determined by counting pits on the wing plate) indicated that it was proportional to the glow intensity. It was found that bubble cavitation is accompanied by high-rate pitting when (hemispherical) bubbles remain on the plate surface. These results suggested [21] that luminescence, noise, and erosion data corresponding to one and the same cavitation regime are correlated. In view of this, it is not without interest to analyze measurement data on cavitation noise and sonoluminescence in relation to the US intensity under variation of duty cycle T/τ of pulses in terms of exponents of power. This should help contrast the SL and US mechanisms in hydrodynamic fields and relate them to specific features of cavitation memory.

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Conflict of interest

The authors declare that they have no conflict of interest.

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