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$1/f$ fluctuations under acoustic cavitation of liquids

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Abstract

A regime of a generation of fluctuations with $1/f$ power spectra under cavitation of liquids in an ultrasonic field has been found experimentally. The acoustic cavitation is accompanied by the formation of various spatial structures and scale-invariant distribution functions of fluctuations. It has been shown that local fluctuations can have non-Gaussian distribution.

A two-dimensional distributed parameter system of stochastic equations describing interacting nonequilibrium phase transitions has been investigated numerically. It has been shown that the system in a wide range of changing initial conditions and the intensity of external noise is characterized by the $1/f$ behavior of power spectra and scale-invariant distribution functions of fluctuations.

The results of numerical simulation agree qualitatively with the experimental data.

Keywords: Self-organized criticality; Acoustic cavitation; $1/f$ fluctuations; Noise; Power spectra; Nonequilibrium phase transitions

1. Introduction

The propagation of high-intensity sound waves in a liquid gives rise to acoustic cavitation. The complicated character of interaction of forming vapor-gas bubbles between each other and with an acoustic field may result in formation of various spatial structures. Dendritic structures of vapor-gas bubbles which look like fractal clusters have been found experimentally at the origination of standing waves in an ultrasonic field. Such structures were denoted as Acoustic Lichtenberg Figures [1,2]. Ref. [2] suggests a theoretical model by which in a system of cavitation bubbles in an acoustic field there arises an instability leading to spatial self- organization. If the dimensions of ultrasonic radiator are commensurable with the sound-wave length, quasi-two-dimensional clusters may form in the vicinity of the radiator surface [3]. The complicated character of interaction of cavitation cavities between one another and with acoustic waves in an experimental cell may result in the formation of bistability and transitions between stationary states [4,5].

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The formation of cavitation clouds may be regarded as nonequilibrium phase transitions in a complicated system of interacting cavitation cavities and acoustic waves. In an acoustic field there forms a stationary random process with nonequilibrium phase transitions, whose power spectrum may have the $1/f$ form [6]. Random processes with the power spectrum inversely proportional to frequency are characterized by the scale-invariant distribution of fluctuations. The scale invariance may be connected with the critical behavior or self-organization in complicated systems [7]. There are a lot of attempts to explain a possible mechanism of generation of scale-invariant fluctuations on the basis of the conception of self-organized criticality [7,8], which is used for describing complicated systems with developed fluctuations.

Investigations of random processes in crisis regimes of liquid boiling have shown that fluctuations with a $1/f$ spectrum and self-organization of a critical state may arise as a result of interaction of subcritical and supercritical nonequilibrium phase transitions in the presence of white noise [9–11]. The extended critical behavior of fluctuations in this case is characterized by self-similar distribution of the probability density, that does not vary with time [11].

This paper presents the results of experimental study of fluctuations under the liquid cavitation in an ultrasonic field. Also, it generalizes the previously suggested theoretical model of $1/f$ fluctuations at nonequilibrium phase transitions to two-dimensional space-distributed system [12,13].

2. Experiment

Experiments were carried out with the use of a source of ultrasonic vibrations with a frequency of 22 kHz. The radiator was placed in an optical cell with water or glycerin. The diameter of the radiator was about 1.5 cm. Cavitation was caused by an increase in the radiator power. With changed radiation intensity in the cell resonance phenomena were observed which led to a change in the pattern created by interacting cavitation bubbles.

At a low radiator power, separate cavitation centers originated at its surface (Fig. 1a). As a result of mutual attraction, bubbles lined up in chains. The number of cavitation centers increased with increasing power. The cooperative interaction of bubbles in the vicinity of the radiator surface resulted in the formation of aggregate reminiscent of fractal clusters (Fig. 1b). A vapor-gas flow was directed from the periphery to the center of a cluster. Separate clusters were able to break away from the surface and pass into the liquid volume. In experiments with glycerin, forming aggregates were more long-lived and have a more contrasting appearance. With a further increase in the power, the interacting cavitation centers formed a critically fluctuating surface (Fig. 1c).

The dynamics of fluctuations in a cavitation cloud was investigated by the method of laser photometry. A laser beam was passed through the optical cell with the liquid under investigation. The diameter of the beam was about 1 mm. The intensity of the passed laser radiation was registered with a photodiode, assigned a numerical value and stored in a computer. Power spectra were determined from time series by Fast Fourier Transform method. To investigate the spectra of a random process under cavitation the laser beam was passed through different parts of the cavitation region. The results obtained depended slightly on the part of the cavitation cloud into which the beam was directed. In the initial stage of cavitation the power spectrum of the photocurrent fluctuations as well as the spectrum of acoustic emission, in the low-frequency region, had the form of white-noise spectrum. With an increase in the radiator power and a certain variation of the frequency the fluctuation intensity increased abruptly, and transitions between two levels of the oscillations were observed. Fig. 2 shows the power spectrum for fluctuations in the indicated regime. From the figure it is seen that the $1/f$ behavior is traced over more than four orders of the power change.

Fig. 3a (1) gives an experimental time series and Fig. 3b (1) the fluctuation distribution function. The bimodal character of the distribution function showed itself clearly under the scale transformations of fluctuations. Roughened time series were created from those measured experimentally by means of averaging by a certain time scale τ in accordance with the formula

$$y_j^{(\tau)} = \frac{1}{\tau} \sum_{i=\tau j}^{\tau(j+1)-1} x_i, \quad 0 \leqslant j \leqslant N/\tau, \tag{1}$$