Experimental observation of stochastic self-oscillations in the electron beam—backscattered electromagnetic wave dynamic system

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We report experimental results that show the existence of a sequence of a small number of bifurcations in an electron beam—backscattered electromagnetic wave system where the current is increasing. This culminates in the occurrence of self-oscillations with a continuous spectrum.

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Recently, the question of stochastic self-oscillations in distributed dynamic systems of a different physical nature has been studied.[1–5] Stochastic self-oscillations are characterized by a continuous spectrum, relatively high intensity and conform to the laws of similitude established on the basis of equations of dynamics of the system in question.[1)] The best known example of stochastic self-oscillations is hydrodynamic turbulence (similitude criteria of flows—equality of the corresponding Reynolds numbers).

In a number of recent works, both theoretical[1] and experimental[2] (see also reviews[3,4]) arguments were put forward in favor of the fact that transition to turbulence in hydrodynamic systems with increasing Reynolds number occur after a small number of bifurcations, whereas an earlier Landau scenario[6] considered turbulence to be the result of successive occurrence of a large number of motions with incommensurable frequencies. "Turbulence" (stochastic self-oscillations) is a typical phenomenon occurring in a very broad class of distributed dynamical systems.[1]

We present experimental data which attest to the occurrence of stochastic self-oscillations in a electron beam—backscattered electromagnetic wave system.

The system under study constitutes a section of an electrodynamic transmission line that is matched at the ends and permeated by an electron beam. The beam interacts with the wave whose phase velocity v_{ph} is similar to the electron velocity v_0, and the group velocity v_g is directed toward the beam. The output signal was taken from the end of the line where the beam was injected. Theoretical analysis shows,[7] allowing for the use of several simplifying assumptions, that the dynamics of such a system is defined by a single dimensionless parameter

$$l = \beta L \sqrt[3]{IK/4U},$$

where $\beta = 2\pi f/v_{\mathrm{ph}}$; f is frequency at which synchronism occurs between the electrons and wave: $v_0 = v_{\mathrm{ph}}(f)$; I is the beam current; U is the accelerating voltage; K is a parameter with dimensions of a resistance which relates the wave power P to the

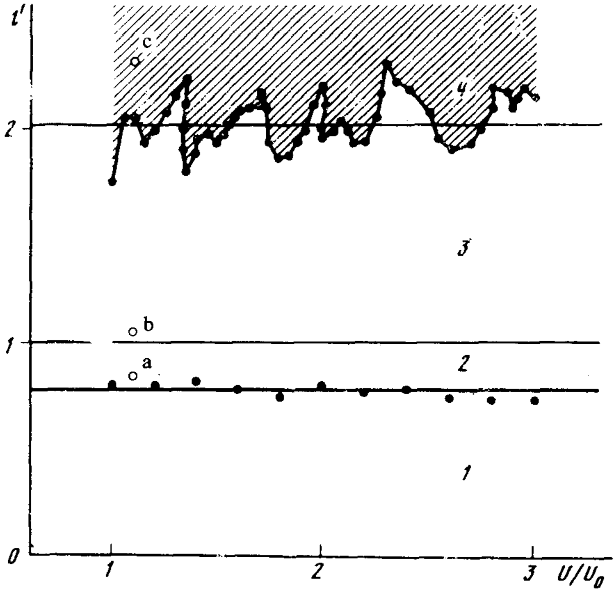

FIG. 1. Regions of existence of various regimes in the system: 1—without generation, 2—monochromatic self-oscillation, 3—self-modulation, 4—stochastic self-oscillations. Points denote region boundaries found experimentally; solid lines—results of averaging. Crosses correspond to regimes in Fig. 2.

amplitude of the longitudinal component of its electric field E: $P = E^2/2\beta^2K$. We shall also use the modified parameter $l' = l/l_M$, where l_M corresponds to occurrence of self-modulation[7,8] (see also Figs. 1 and 2b). According to theory,[7] $l_M \approx 2.9$.

Several bifurcation transitions could be observed in the experiment for various values of voltage U by increasing the beam current (Figs. 1 and 2).

Self-oscillations are nonexistent at $l' \lesssim 0.8$, At $0.8 \lesssim l' < 1$, they occur with a frequency near f (Fig. 2a). At $1 < l' \lesssim 2$, multi-frequency oscillations are observed—automodulation,[7,8] (Fig. 2b). Frequency difference between the neighboring spectral componets (modulation frequency) is of the order of magnitude, and the frequency f_M increases slightly with increasing current.[2)] At $l' > 2$ stochastic self-oscillations appear (Fig. 2c). Their relative intensity may be judged by comparing the existing photographs to each other. The intensity of these oscillations is high; the law of similitude is adequately satisfied (in Fig. 1 points that correspond to occurrence of stochastic self-oscillations at different values of U lie near the line $l' =$ const); evidence of an effective synchronization when an external harmonic signal is introduced (moreover, stochastic self-oscillations become disrupted and a self-modulation regime sets in) permits one to affirm that oscillations with a continuous spectrum are constrained by the dynamic properties of the system but not by the amplification of small fluctuations.

Thus, stochastic self-oscillations are observed in a electron beam—backscattered electromagnetic wave system at sufficiently large values of parameter l ($l > l_{cr} \sim 6$). The nature of transition of the system into this regime as l increases apparently supports the Ruelle-Takens concept.[1] We should note that the bifurcations that directly precede the occurrence of stochastic self-oscillations (see footnote 2) are clearly sensitive to small perturbations of the system and are, therefore, not universal in nature. We

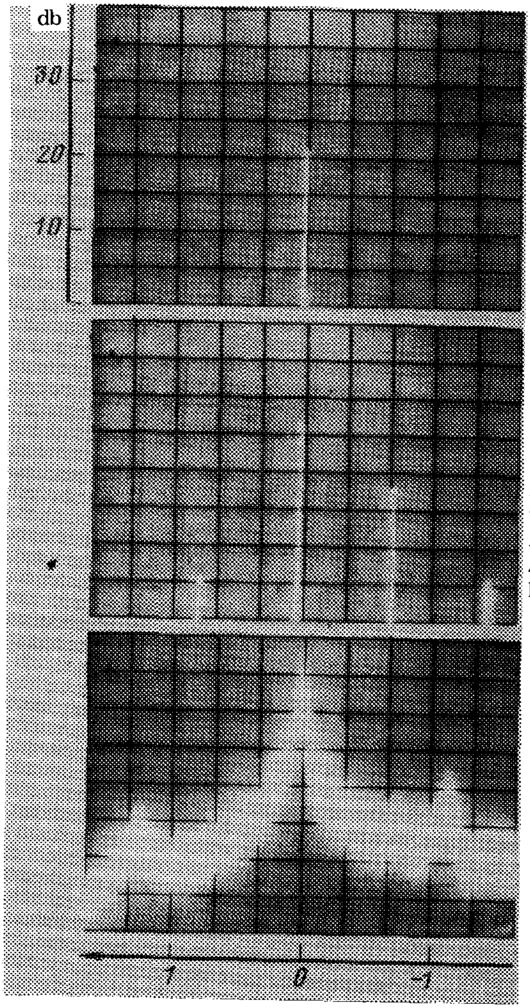

FIG. 2. Spectrum of output signal from the system in regimes designated by crosses in Fig. 1. Abscissa shows normalized frequency detuning $\Delta f(L/v_0 + L/v_{\rm bound})$. Ordinate scale is logarithmic.

should emphasize in this connection that the regime of stochastic self-oscillations was stable and evident in the region (cross-hatched area in Fig. 1) up to the highest attainable currents.

[1)]The latter is important since it permits us to differentiate stochastic self-oscillations from the case where the continuous spectrum depends on the amplification of microscopic fluctuations in a given system.

[2)]A large number of bifurcations could be observed in the region $1 < I' \lesssim 2$, their character being dissimilar at different accelerating voltages and for different conditions of injection of the electron beam. At times, transition to stochastic self-oscillation regime was preceded by occurrence of modulation at freuqencies $f_M/2, f_M/3$, etc. At other times, oscillations with continuous spectra were observed and sustained in small intervals of current variations. These observations clearly agree with the picture described by Arnol'd.[9]

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