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Adaptive control of non-synchronous oscillations in a network of identical electronic neuron-like generators

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In a radio physical experiment, a control scheme is implemented that makes it possible to desynchronize oscillations in networks of identical electronic neuron-like generators with a random topology of additive and diffusive couplings.

Keyword: Neuron-like generators, Synchronization, Adaptive control, Radio physical experiment.

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The synchronizing adjustment of rhythms of interacting self-oscillating systems is typical of animate and inanimate objects [1]. The examination of synchronization processes in networks of coupled oscillators is relevant to various branches of science and attracts much research attention [2]. Specifically, numerous biological and physiological systems exhibit synchronization of their elements. For example, synchronization effects are central to motor functioning [3,4], healthy functioning of the cardiovascular system [5], and cognitive brain functioning [6]. However, excessive synchronization of neurons in the brain may lead to such serious neurological diseases as epilepsy [7], schizophrenia [8], and Parkinson's disease [9]. Therefore, the issue of desynchronization of oscillations in neural networks is of much interest.

Different methods relying on linear [10] and nonlinear [11] delayed feedback and mean-field inversion [12] have been proposed for disrupting the synchronization regime in networks of coupled oscillators. All these methods have been developed for networks of oscillators that are coupled globally via a mean field. Other types of oscillator coupling (e.g., additive and diffusive coupling) are often found in real-life multielement networks. The issue of desynchronization of oscillations in neural networks with a random topology of such couplings has been examined numerically in [13], and the desynchronization conditions for a network of diffusively coupled oscillators have been determined analytically in [14] based on the Yakubovich oscillatority concept. In the present study, we report the results of the first successful radiophysical experiment on desynchronization of synchronous oscillations in a network of electronic neuron-like generators having a random topology of additive and diffusive couplings with the use of adaptive control of oscillatory regimes.

Let us first consider a neural network consisting of additively coupled neuron-like FitzHugh–Nagumo oscillators [15] with their dynamics characterized by model equations of the following form:

$$\varepsilon \dot{u}_i(t) = u_i(t) - \frac{u_i^3(t)}{3} - v_i(t) + \sum_{j=1}^{N} k_{i,j} u_j(t) + c(t),$$

$$\dot{v}_i(t) = u_i(t) + a, \qquad (1)$$

where $u_i(t)$ and $v_i(t)$ are dynamic variables of the ith oscillator, $i = 1, \ldots, N$ is the oscillator index number, N is the overall number of oscillators, ε is the time-scale parameter that is typically small, a is the threshold parameter, $k_{i,j}$ is the coefficient of coupling acting in the direction from oscillator j to oscillator i, and $c(t)$ is the external control signal. We consider the case of identical oscillators (1) that are engaged in periodic self-oscillations in the absence of couplings and control signal (i.e., the case of $a < 1$) [15].

Coefficients $k_{i,j}$ characterize the architecture and strength of couplings in a network. If all $k_{i,j} \neq 0$, all oscillators in a network are coupled via mean field $\bar{u}(t) = N^{-1} \sum_{j=1}^{N} u_j(t)$, and their oscillations synchronize if the coupling is sufficiently strong. This synchronization may be disrupted by applying a control signal in the form of a mean-field signal with a reverse sign to them [12]. A similar approach may be used to desynchronize network (1) that lacks a fraction of interoscillator couplings. However, control signal $c(t) = -k_m D\bar{u}(t)$ [13], where k_m is the greatest of all coefficients $k_{i,j}$ and D is the mean number of oscillators affecting each network element, should be applied in this case.

We have constructed an original analog-digital setup to control oscillations in a network of coupled identical neuron-like oscillators in a radiophysical experiment. The studied network consisted of ten analog electronic FitzHugh–Nagumo generators exhibiting neuron-like dynamics. Their schematic circuit diagram has been detailed

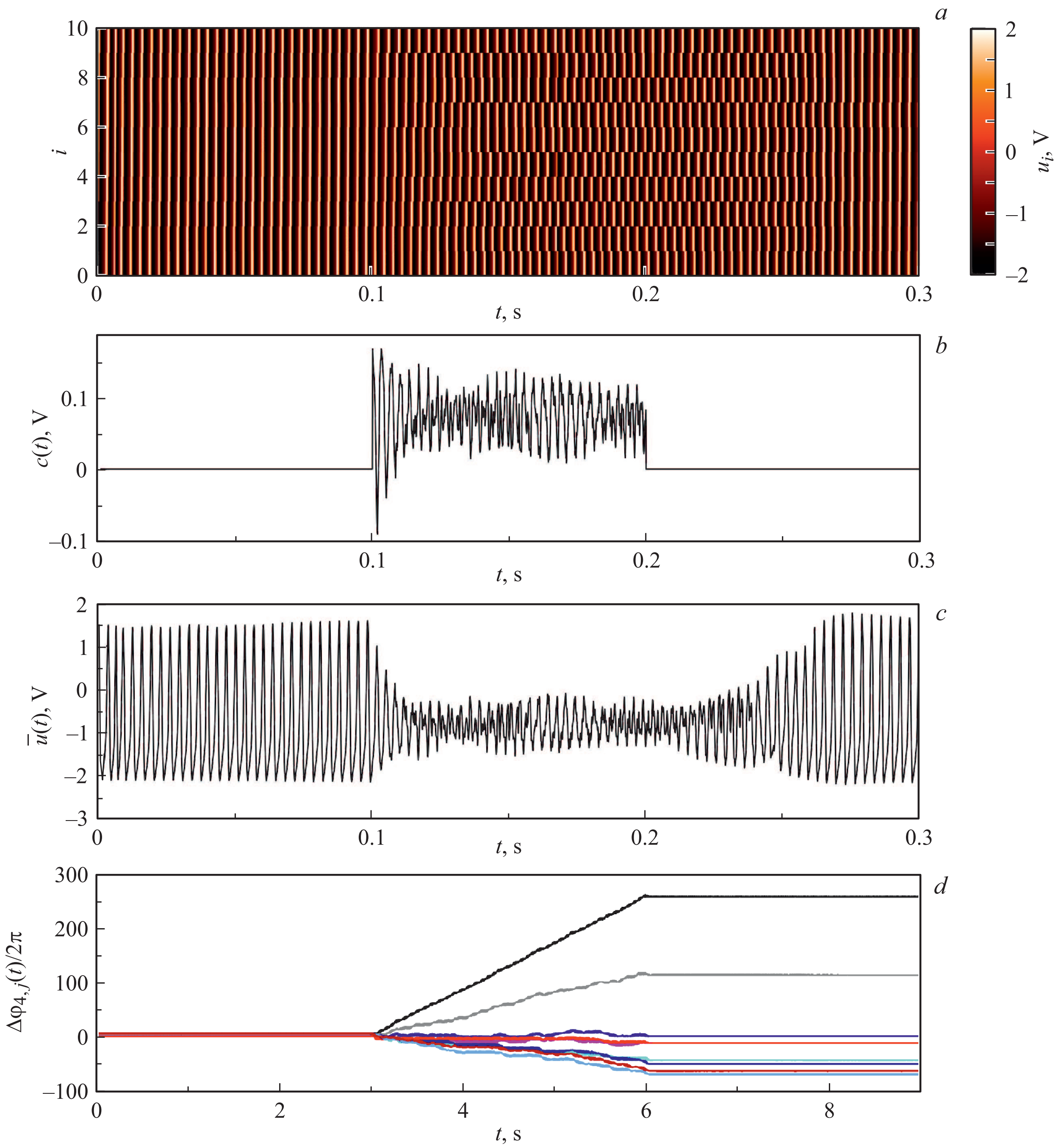

Figure 1. *a* — Spatiotemporal diagram of oscillations of variables $u_i(t)$ of additively coupled generators (1). *b* — Control signal $c(t)$. *c* — Temporal dynamics of mean field $\bar{u}(t)$. *d* — Temporal dynamics of phase differences $\Delta\varphi_{4,j}$ (normalized to 2π) between the fourth generator and the other nine generators.

in [16]. A software approach to shaping the signals governing the coupling between analog generators was used to implement this coupling [17]. In accordance with this approach, voltage signals from the output of each generator are fed to a multichannel analog-to-digital converter and digitized. These signals are then transformed in a LabView application, and signals of the needed shape, which establish generator coupling, are formed. Control signal $c(t)$ is added to each coupling signal in accordance with Eq. (1). The signals shaped this way are processed by a multichannel digital-to-analog converter and fed to the input of each generator. This approach provides an opportunity to set arbitrary architecture and type of couplings between generators and adjust the control signal in real time.

Figure 1, *a* presents the spatiotemporal diagram of oscillations of variable $u_i(t)$ in each of the ten generators with parameters $\varepsilon = 0.1$, $a = 0.8$, $D = 4$, and $k_m = 0.02$ and $k_{i,j}$ values distributed uniformly within the [0;0.02] interval.

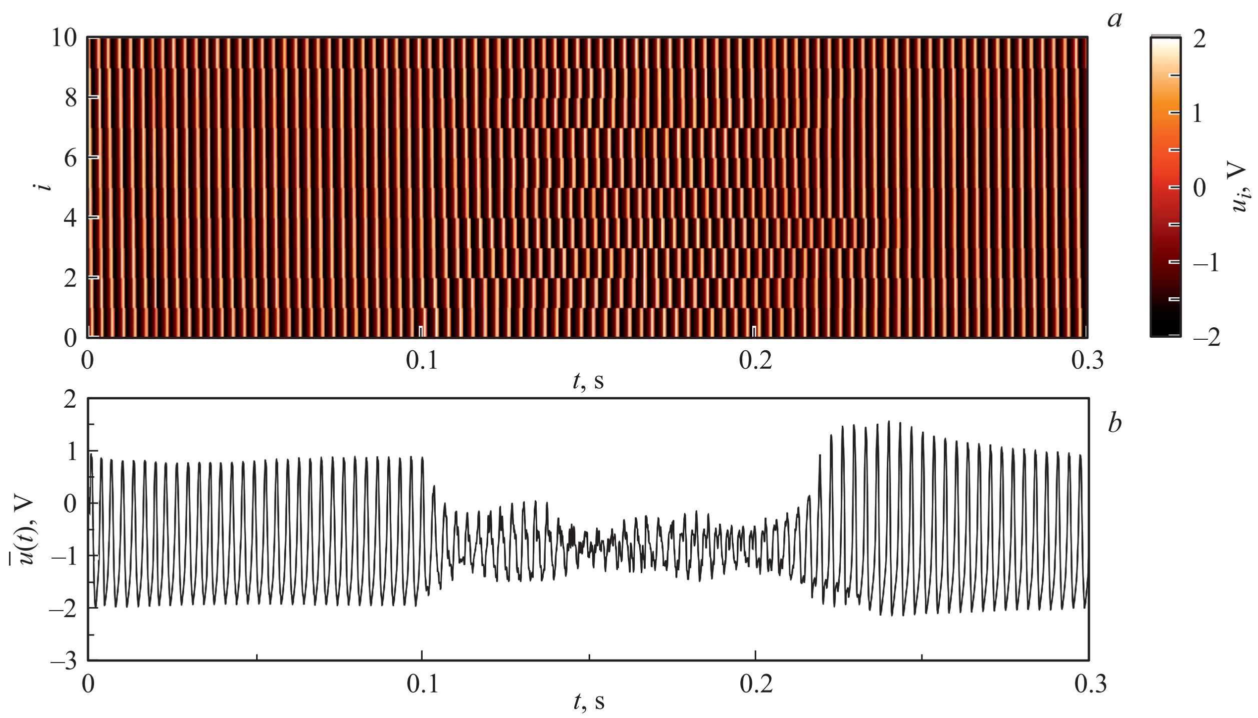

Figure 2. *a* — Spatiotemporal diagram of oscillations of variables $u_i(t)$ of diffusively coupled generators (2). *b* — Temporal dynamics of mean field $\overline{u}(t)$.

Control signal $c(t) = 0$ within the first 0.1 s (Fig. 1, *b*). All generators remain synchronized during this time period. However, since the analog elements of generators cannot be exactly identical, $u_i(t)$ oscillation amplitudes of generators differ slightly (Fig. 1, *a*). Note that both the amplitudes and the frequencies of self-oscillations of electronic generators differed in the case of $k_{i,j} = 0$ (i.e., without couplings) and took the values of 2.077 ± 0.004 V (mean $\pm$ standard deviation) and 287.4 ± 5.1 Hz, respectively. Within the interval from $t = 0.1$ to 0.2 s, the control signal disrupts synchronization, and the $u_i(t)$ values become non-synchronous (Fig. 1, *a*). The control signal at the last 0.1 s is again set to $c(t) = 0$ (Fig. 1, *b*), and generator synchronization in the network is restored following a transient process (Fig. 1, *a*).

Figure 1, *c* presents the temporal dynamics of mean field $\overline{u}(t)$. Within the synchronization region ($t \in [0; 0.1]$ s), $\overline{u}(t)$ oscillates with a nearly constant amplitude that is comparable to the amplitude of $u_i(t)$ oscillations and has deviation $\sigma = 1.45$. When the control signal is present (at $t \in [0.1; 0.2]$ s), $\overline{u}(t)$ undergoes irregular oscillations with a significantly smaller amplitude and features deviation $\sigma = 0.15$. The amplitude of $\overline{u}(t)$ increases again after the control signal is switched off. These data agree well with the results of numerical studies of oscillator networks coupled globally via a mean field, where the mean-field deviation was demonstrated to be close to zero at high N values in the non-synchronous regime and to increase markedly after synchronization [10,11].

Phase difference $\Delta\varphi_{i,j}$ between any pair of generators remains almost constant in the case of synchronization; in the non-synchronous regime, it may vary (increase or decrease without restrictions). Since $\Delta\varphi_{i,j}$ does not have enough time to change considerably in the non-synchronous regime within the interval of application of the control signal in Figs. 1, *a*–*c*, we plotted a different graph where the on and off intervals of $c(t)$ are extended from 0.1 to 3 s (Fig. 1, *d*). It can be seen that the synchronization of oscillations is disrupted in the presence of the control signal at $t \in [3; 6]$ s.

Let us now consider diffusively coupled FitzHugh–Nagumo generators characterized by the following equations:

$$\varepsilon\dot{u}_i(t) = u_i(t) - \frac{u_i^3(t)}{3} - v_i(t) + \sum_{j=1}^{N} k_{i,j}\big(u_j(t) - u_i(t)\big) + c_i(t),$$
$$\dot{v}_i(t) = u_i(t) + a. \quad (2)$$

In contrast to the case of additive coupling, the application of the same control signal $c(t) = -k_m D\overline{u}(t)$ to all generators results in suppression of oscillations in generator network (2) [13]. In order to disrupt synchronization while retaining oscillatory activity, one needs to apply different signals to different generators: $c_i(t) = k_m D\big(u_i(t) - \overline{u}(t)\big)$ [13].

Figure 2, *a* presents the spatiotemporal diagram of $u_i(t)$ oscillations in each of the ten generators with the same parameters that were used in Fig. 1, *a*. The duration of on and off intervals of the control signal is 0.1 s. With the control signal switched on in the middle section of the plot ($t \in [0.1; 0.2]$ s), the values of $u_i(t)$ desynchronize (Fig. 2, a), and the amplitude of mean field $\bar{u}(t)$ decreases markedly relative to the $\bar{u}(t)$ amplitude in the synchronization region ($t \in [0; 0.1]$ s) (Fig. 2, b). When the control signal is switched off at $t = 0.2$ s, generator synchronization in the network is restored following a transient process.

Thus, control over non-synchronous oscillations was established in a radiophysical experiment in a network of identical electronic neuron-like generators with a random topology of sparse couplings. It was demonstrated that a control signal common to all generators may be used to disrupt synchronization in a network of additively coupled generators, while different control signals need to be applied to different generators in order to achieve desynchronization in a diffusively coupled network.

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Conflict of interest

The authors declare that they have no conflict of interest.

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