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Inducing and destruction of chimeras and chimera-like states by an external harmonic force

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ABSTRACT

We study the phenomena of chimera destruction and inducing of chimera-like states in an ensemble of nonlocally coupled chaotic Rössler oscillators under an external harmonic force. The localized harmonic influence can lead to both destruction and changing of the spatial topology of chimeras. At the same time this influence can cause the emergence of stable chimera-like states (*induced chimeras*) for the regime of partial coherent chaos. Induced chimeras are also observed for the global influence. We show the possibility of controlling the chimera-like state topology by varying the parameters of localized external harmonic influence.

0. Introduction

Recently, the study of chimera states is one of the popular scientific directions in different research fields. The chimera represents a special structure occurring in ensembles of identical oscillators as a result of partial synchronization. Its distinct feature is the coexistence of two types of clusters, which are called as coherence and incoherence clusters. Oscillators of an coherence cluster have similar instantaneous states, while instantaneous states of elements from an incoherence cluster significantly differ from each other and their spatial distribution is irregular. The first similar structure has been found in 2002 by Y. Kuramoto in [1]. After that a lot of works have been devoted to study chimera states, for example [2–7]. Usually, chimera states are observed in ensembles with nonlocal interaction. They can also exist for the case of global coupling (for instance, [8–10]) and even for local coupling (see [11–13]). Moreover, so-called virtual chimeras have been found in systems with delayed feedback [14,15]. The chimera has been observed in the number of experiments [14–22]. The interest in studying chimera states is associated with the fact that they can be encountered in different systems of coupled nonlinear elements. Apparently, chimeras can play an important role in the nature and technique, for example, in energetic systems, the population dynamics, and even in the brain functioning.

One of the important issues in exploring chimera structures is its control by external forces. However, the influence of external forces on the stability and features of chimeras is still a poorly studied issue. There are several works where the noise effect on chimeras has been explored. The impact of external noise on the lifetime of amplitude chimeras has been studied in the ensemble of nonlocally coupled harmonic oscillators in [23]. These states represent metastable structures. For this reason the random influence noticeably reduces their average lifetime. Beside this, chimera states are observed in experiments where the noise is inevitably present. Consequently, some chimera types are stable enough to the random influence, for example, the phase chimera in a ring of nonlocally coupled logistic maps [24]. Metastable amplitude chimeras also exist in the same system and their lifetime can be increased by external noise [24] in contrast to the case in [23]. Another example of the chimera stabilization with noise is given in [15]. In certain cases, noise is a necessary condition for the emergence of chimera states, for instance [25]. Generally, there are a lot of unclear aspects in regard to the influence of noise on various types of chimera states.

The impact of periodic external force on chimera states has not almost been studied. We can note only the work [15], in which the synchronization of a virtual chimera by the external periodic force has been revealed. In our work we consider the ensemble of nonlocally coupled chaotic Rössler oscillators with the spatially lo-

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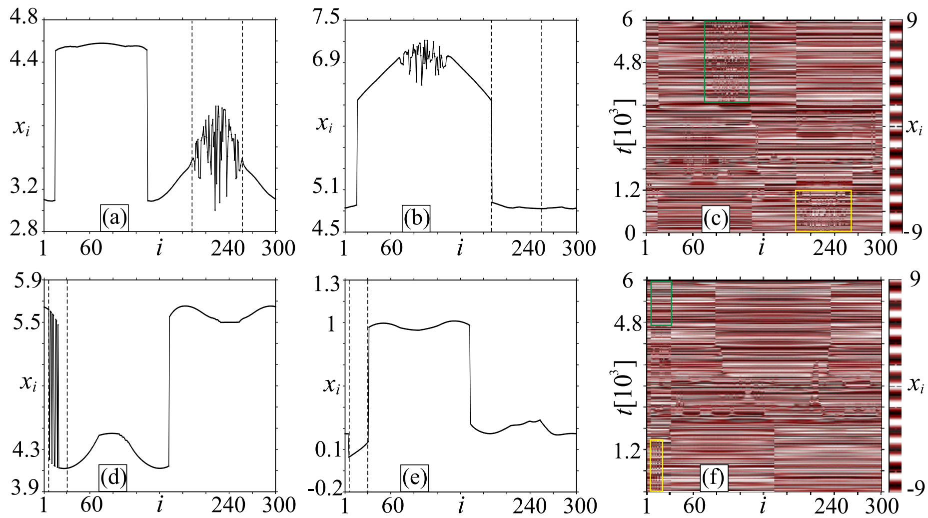

Fig. 1. (Color online.) The localized external influence of the system (1) for two types of the chimera regimes. Plots for the regime of an amplitude chimera for $\sigma = 0.04$: snapshots of the system state (a) without external force, and (b) under influence within $i \in [190; 260]$ with $A_{ext} = 0.005$ ($t = 6000$); (c) space-time plot. Plots for the regime of an phase chimera for $\sigma = 0.044$: snapshots (d) without influence and (e) under influence within $i \in [5; 30]$ with $A_{ext} = 0.009$ ($t = 6000$); (f) space-time plot. Boundaries of the external influence in (a), (b), (d), (e) are highlighted by the dotted lines. The special color scheme is used for the plots (c) and (f). The regions of incoherence clusters are marked in the plots by the frames. Parameters: $f_{ext} = 0.11$, $r = 0.3$, $a = 0.2$, $b = 0.2$, $c = 4.5$, $N = 300$.

calized and global periodic influence. We show that the external harmonic force can be used to suppress and form certain chimera-like structures. In addition, we demonstrate that varying the external influence enables one to control these structures. Thus, we believe that uncovering these effects is an interesting and actual issue.

1. System under study

We study a ring of nonlocally coupled identical Rössler oscillators under the localized external harmonic force. The system under study is described be the following system of differential equations:

$$\begin{aligned}
\dot{x}_i &= -y_i - z_i + \frac{\sigma}{2P}\sum_{k=i-P}^{i+P}(x_k - x_i)\,,\\
\dot{y}_i &= x_i + ay_i + \frac{\sigma}{2P}\sum_{k=i-P}^{i+P}(y_k - y_i) + F_i(t),\\
\dot{z}_i &= b + z_i(x_i - c) + \frac{\sigma}{2P}\sum_{k=i-P}^{i+P}(z_k - z_i)\,,\\
x_{i+N}(t) &= x_i(t),\quad y_{i+N}(t) = y_i(t),\\
z_{i+N}(t) &= z_i(t),\quad i = 1, \ldots N,
\end{aligned} \tag{1}$$

where index i is an index of the ring elements, t is the time variable, a, b, and c are the control parameters of the system (1), σ is the coupling strength, P is a number of the elements, which are coupled with the ith element for each side. The total number of oscillators in the ensemble is equal to $N = 300$. Interaction between the elements has a nonlocal character. The nonlocality degree is determined by a value of $r = \frac{P}{N}$ which is called as a coupling radius. The oscillator parameters are fixed as following: $a = 0.2$, $b = 0.2$, $c = 4.5$. These parameters correspond to the chaotic dynamics of a single Rössler oscillator. The coupling radius is also fixed as $r = 0.3$.

The external harmonic force $F(i, t)$ impacts on the elements of the ensemble (1) within the certain spatial region: $i \in [i_1,\ i_2]$. We call this region as a region of influence in space. The external force is described by the following equation:

$$F_i(t) = \begin{cases} A_{ext} sin(2\pi f_{ext} t), & i \in [i_1; i_2] \\ 0, & i \notin [i_1; i_2], \end{cases} \tag{2}$$

where A_{ext} is the amplitude of harmonic force, f_{ext} is its frequency. So, the same external force impacts on each oscillator within the localized spatial interval $[i_1;\ i_2]$ and the external force is absent outside of this interval.

2. Influence on the chimera states by an localized external harmonic force

It is known that the ensemble of nonlocally coupled chaotic Rössler oscillators (1) without the external force ($A_{ext} = 0$) demonstrates the following regimes for increasing the coupling strength σ, namely the complete desynchronization, chimera states, partial coherence, complete chaotic synchronization (see [3]).

At first, we study the influence of an external localized force on chimera states. All the elements of the incoherent clusters are subjected to influence of the same external harmonic signals. The frequency of these signals is fewer than the average frequency of chaotic self-sustained oscillations in the autonomous regime f_0: $f_{ext} < \langle f_0 \rangle$. There are two types of chimera structures for an ensemble of the nonlocally coupled chaotic oscillators with the Feygenbaum mechanism of transition to chaos. They are called as amplitude and phase chimeras [7]. Primarily, we consider the influence of an external force on the amplitude chimera. Fig. 1(a) represents an example of this structure in the system (1). The influence of a harmonic signal on the incoherence cluster leads to the emergence of a region with a smooth profile within the region of influence in space (adjacent elements behave coherently). Moreover, the chimera does not disappear but it emerges in the new region of space. An example of this regime is shown in Fig. 1(b). The spatiotemporal dynamics is represented in the space-time plot in Fig. 1(c). We use a special color scheme for the space-time plots. It represents multiply alternation of white, red (online), and black lines. This scheme enables us to highlight the regions with incoherent spatiotemporal dynamics. The incoherence cluster of the chimera under the influence exists only the certain time (this spatiotemporal region is marked by the bright (yellow online) frame in Fig. 1(c)). After that this cluster is destroyed. A lot of unstable spatial structures appear during the transient process. Thereafter a

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