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Generating chaos for a class of linear switching control systems: A hybrid approach ☆

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Abstract

This paper investigates a class of linear continuous-time "periodic" switching systems and proposes a new approach to generate chaos by designing a hybrid switching rule. First, Lyapunov exponents of the system are derived by extending the Floquet theorem to a class of linear continuous-time switching systems. Then, a novel switching rule is proposed to gain global boundedness property as well as the required placement of Lyapunov exponents for chaos. A numerical example is given to illustrate the chaotic dynamic behavior of the generated system. Furthermore, the corresponding bifurcation diagrams are sketched, which, together with other phase portraits, clearly verify the validity of the main result.

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1. Introduction

During the last four decades, chaos phenomenon and chaos control have been intensively investigated within the science, mathematics and engineering communities [1–7]. Generally speaking, there are two main streams on chaos researching. Some people have explored methods to avoid chaotic conditions when it might degrade the performance of the entire system, such as distributed artificial intelligence systems [1,8,9]. Other researchers have done exactly the opposite, they have tried to generate chaos. Why did they do this? It comes from the fact that chaos is not just helpful but even fundamental, especially in some engineering fields such as biomedical engineering, resonance prevention in mechanical systems, flow dynamics and liquid mixing, information encryption and secure communication, power systems protection and so on [1]. So, chaotificaiton, or anti-control of chaos, has attracted much attention in these years.

Motivated primarily by the diversity of application, some new chaotic systems have been developed in several ways. First of all, as a paradigm of chaotification, state feedback method has been studied to generate chaos [10–13], people also utilized disturbance to chaotify the corresponding systems [14]. Almost at the same time, Guan et al. [15,16] investigated the way to chaotify discrete systems and complex dynamical networks with impulsive control. Additionally, after the rapid development in more than a decade, multi-scroll chaotic attractors generation has become a relatively mature research direction, the related theories, methodologies and hardware implementation techniques have been reviewed in [17–22]. Furthermore, other related researches such as hyperchaotic attractors [23] and entanglement method [24] have also been reported.

Since there are a lot of applications of chaotification in many fields as mentioned above, it has become a new direction in the study of chaos. It seems that there should be no difficulties to generate chaos at first glance, because many researchers have developed some laying foundation works and theories on chaos. However, the fact is not so [1]. For example, the traditional Silnikov theorem and Melnikov method provide analytic criteria for proving the existence of chaos in high-dimensional autonomous systems. But they are difficult to apply in practice. So it is easier to find a system which is chaotic, conversely, chaotification is not easy to implement in systematic ways with a fundamental mathematical frame due to no unified criterion for what is chaos. Furthermore, most existing theories are based on discrete systems, continuous efforts are devoted to seek a unified theory and some kinds of canonical forms for continuous-time systems nowadays.

But new design approaches and rigorous proofs are still needed in the research on chaotification for continuous-time systems. Among those new design approaches, switching control is a useful and attractive tool. As it is known, switching dynamical systems are hybrid systems with both continuous dynamics and discrete dynamics. With the joined efforts [17,18,25–27], approaches generating chaos or (multiscroll) chaotic attractors based on the concept of switching control had been gradually put forward. After that, many researches on generating chaos from switching systems were presented [28–34]. Among these works, Lü [28] reviewed several approaches for generating multi-scroll chaotic attractors from some 2D and 3D linear autonomous systems with a simple piecewise linear or piecewise constant switching controller. Zheng [29] introduced a switching controller for chaos generation, which can simultaneously generate two symmetrical chaotic attractors. Then, a chaotic system was designed to generate two opposite direction attractors in a wide parameter range by a switching piecewise-linear controller [30]. Liu [31] showed that chaos or chaos-like behavior could be generated by applying an appropriate switching rule for switched systems. Zhao [32] extended Marotto's theorem to derive the condition for the existence of chaos in the sense of Devaney and showed