Chapter 15
Radio Frequency Chaotic Circuit Design:
From Theory to Practice

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ABSTRACT

In recent decades the design of nonlinear circuits, which are capable of generating chaotic oscillations from audio frequencies up to the optical band, is a great challenge due to their use as sources of chaotic carriers in a variety of applications. Therefore, this chapter is dedicated to this class of circuits. A brief history of the first nonlinear circuits, which were the most important stages in the evolution of chaotic circuits, is given at the beginning of the chapter. Next, one of the most well known nonlinear circuits, the circuit of Colpitts oscillator, and its modifications, operating from a few Hertz up to the microwave region, are described in detail. A novel modification of Colpitts oscillator, which has higher fundamental frequency than the others do and greater Lyapunov dimension is also studied. Finally, some interesting applications of this class of circuits are presented at the end of this chapter.

INTRODUCTION

One of the most significant scientific revolutions in the previous century was the foundation of chaos theory. The study of chaos may be said to have started with the pioneering work of the French mathematician Henri Poincaré in 1880. Poincaré's motivation was partly provided by the problem of the orbits of three celestial bodies experiencing mutual gravitational attraction. By considering the behavior of orbits arising from sets of initial points, Poincaré was able to show that very complicated orbits (now these orbits called chaotic) were possible (Poincaré, 1890). In 1898 Jacques Hadamard published an influential study of the chaotic motion of a free particle gliding frictionlessly on a surface of constant negative curvature (Hadamard, 1896). In the system

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studied, "Hadamard's billiards", Hadamard was able to show that all trajectories are unstable in that all particle trajectories diverge exponentially from one another.

Much of the earlier theory was developed almost entirely by mathematicians, under the name of ergodic theory. Later studies, also in the topic of nonlinear differential equations, were carried out by Birkhoff (1927), Kolmogorov (1941), Cartwright and Littlewood (1945) and Stephen Smale (1960). Except for Smale, these studies were all directly inspired by physics: the three-body problem in the case of Birkhoff, turbulence and astronomical problems in the case of Kolmogorov, and radio engineering in the case of Cartwright and Littlewood.

The main catalyst for the development of chaos theory was the electronic computer. Much of the mathematics of chaos theory involves the repeated iteration of simple mathematical formulas, which would be impractical to be done by hand. Electronic computers made these repeated calculations practical, while figures and images made it possible to visualize these systems. An early pioneer of the theory was the meteorologist Edward Lorenz whose interest in chaos came about accidentally through his work on weather prediction in 1961 (Lorenz, 1963). Lorenz, who was using a simple digital computer to run his weather simulation, had discovered that small changes in initial conditions produced large changes in the long-term outcome. Also, chaos was observed by a number of experiments before it was recognized; e.g., in 1927 by van der Pol (1927) and in 1958 by Ives (1958).

After Lorenz, a large number of scientists noticed the signs of chaos in a plethora of dynamical systems revealing its basic principles. As dynamical system, a physical phenomenon that evolves in time, is meant. In mathematical terms, the states of the system are described by a set of variables and its evolution is given by a set of differential equations with the values of the initial states. This is summarized in Equation (1),

$$\frac{dX_i(t)}{dt} = F_i(X_j(t), \Lambda) \tag{1}$$

where $X_i(t) \in R^N$ is the coordinate i of the state of the system at instant time t, that is X is an N-dimensional vector, $i, j = 0, 1, \ldots, N$ with $N \geq 1$, F is a parametric nonlinear function that describes the evolution of the system and Λ is the vector of parameters that controls the evolution of the system. It is observed that this kind of systems is deterministic, thus the time evolution of X can be calculated with F and Λ from a given initial state X_0. In continuous-time dynamical systems, t takes continuous values, corresponding to the evolution of the system's dynamic behavior in time.

So, a dynamical system of Equation (1), in order to be considered as chaotic, must fulfill three basic conditions (Hasselblatt, 2003).

- It must be topologically mixing,
- Its periodic orbits must be dense, and
- It must be very sensitive on initial conditions.

The term topologically mixing means that the chaotic trajectory at the phase space will move over time so that each designated area of this trajectory will eventually cover part of any particular region. The second feature of chaotic systems is that their periodic orbits have to be dense, which means that, the trajectory of a dynamical system is dense, if it comes arbitrarily close to any point in the domain. Finally, the third and probably the most well-known feature of chaotic systems, is the sensitivity on initial conditions, which is mainly known as the "butterfly effect". This means that a small variation on a system's initial conditions will produce a totally different chaotic trajectory.

Today, everybody knows that chaos is a phenomenon which appears widely and naturally in many dynamical systems and its study has led to a vast multidisciplinary research field, ranging from the natural sciences (meteorology chemistry,

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