Foreword

Today we can say with certainty that both scientists and engineers have widely recognized the need to use the fractals theory along with the theory of fractional integral-differential operators and fractal treatment to solve a variety of problems that emerge in various fields of modern science and technology. Terms “fractals” and “fractal” reflect the modern view of the physical nature of real objects and processes; this view was firmly established after publication of the pioneering works of B. Mandelbrot about fractal geometry of the Nature.

The “fractional operators” reflect the modern approach to mathematically describe and identify the properties of fractal objects and processes that used to be described by integer order differential equations. Today we cannot but describe these objects and processes using the non-integer (fractional) order equations that fill the gaps between equations of the first, the second, and other integer orders.

Despite the fact that the concept of fractional derivatives was known as early as the end of the seventeenth century, systematic use of fractional calculus in science and technology actually can be attributed to the time of appearance of the pioneering works by Rashid Shakirovich Nigmatullin, the founder and the scientific director of the Kazan scientific school of investigation and application of electrochemical converters of information (ECCI), and his students.

R. Sh. Nigmatullin was *The First* to physically implement fractional integration and differentiation (FID) operations on the basis of real elements (in particular, electrochemical ones). He also was the first to develop methods for synthesis of ladder-type resistive-capacitive and resistive-inductive circuits that implement these operations. He proposed a number of certain useful applications of such elements, in particular, to increase the resolution of oscillopolarographic spectrum. It was further widely used to develop the corresponding devices both in Russia and abroad.

R. Sh. Nigmatullin has also offered the block diagram of a computer meant for solving equations of linear, spherical, and cylindrical diffusion. The device is based on operational amplifiers with special RC two poles (fractional-order integrators and differentiators). He showed the possibility to use the semi-infinite RC cable in order to create some special functions out of the trigonometric. All these results were obtained and published within the period from 1962 to 1968.

Appearance of the following works has ultimately established interest in fractional calculus: well-known works of Oldham K.B. (e.g., Oldham KB, Spanier J. The Fractional Calculus. New York: Academic Press, 1974. 234 p.), of B.B. Mandelbrot (Mandelbrot B.B. Les Objects Fractals: Forme, Hasard et Dimension. Paris: Flammarion, 1975. 187 p.; Mandelbrot B.B. Fractals: Forme, Chance and Dimension. San-Francisco: Freeman, 1977. 365 p.; Mandelbrot B.B. The Fractals Geometry of Nature. NY: Freeman, 1982. 468 p.), and the fundamental book of S.G. Samko, A.A. Kilbas and O.I. Marichev (S.G. Samko, A.A. Kilbas, O.I. Marichev Fractional Order Integrals and Derivatives and Some of Their Applications. Minsk: Nauka I Tekhnika, 1987. 688 p.).

It took fractional calculus mathematics a historically short period to find application in various fields of science, such as classical and quantum physics, field theory, electrodynamics, solid state physics, fluid dynamics, turbulence, general chemistry, biology and medicine, stochastic analysis, nonlinear control theory, image processing, seismology, geology, and social sciences. Numerous scientific publications and monographs approve this fact. Here are just three of them. The first is the monograph by A.A. Potapov (Fractals in Radiophysics and Radar: Sample Topology. M.: Universitetskaya kniga, 2005. 848 p.). The second is the monograph by V.V. Uchaikin (The Method of Fractional Derivatives. Ulyanovsk: “Artichoke” publishers, 2008. 512 p.). Each monograph contains more than 1000 references. And the third one is the following fundamental book: The Modern Image Processing Techniques (authors: A.A. Potapov, Y.V. Gulyaev, S.A. Nikitov, A.A. Pakhomov, V.A. German)/Ed. by A.A. Potapov. M.: FIZMATLIT, 2008. 496 p.

Another indicator of great interest in fractional analysis and its applications is the fact that a variety of international conferences on these issues are conducted annually. For example, representative conferences “Fractional differentiation and its applications” (FDA’ 02, FDA’ 04, FDA’ 06, FDA’ 08, FDA’ 12, FDA’ 14, FDA’ 16 etc.) were organized by specialized scientific magazines, such as *Chaos, Solutions and Fractals*, *Nelineyny mir* (Nonlinear world), and *Journal of Fractional Calculus and Applied Analysis* (Bulgaria).

However, the Russian science, not to mention the industry, demonstrates absolutely insufficient use of these concepts and of emerging opportunities to understand the Nature and acquire new knowledge, to create new methods and measurement tools, and to create better models of technical equipment. One reason for this is that there is not enough scientific-technical and especially educational literature that would reflect both theoretical understanding of fractional differentiation and integration operations and their hardware implementation along with practical use. That is why scientists and engineers do not have the required knowledge on fractional analysis as well in the field of design of fractional-order elements (“fractal elements”) that would make it possible to physically implement fractional operators and other devices for information and signal processing.

This book is the result of systematized outcomes of theoretical and experimental research works of the authors. The book partly fills the mentioned gap. The book can be used to develop general engineering and special education courses along with the corresponding teaching materials. The aim is to actively introduce the concepts of fractal geometry and fractional analysis into the minds of the future engineering professionals and scientists who would be able to work at the production industry and in research laboratories and would be able to embody these ideas into new instruments, devices, and systems.

Chapter 1 summarizes the fundamentals of the fractals theory, fractal dimension, and scaling. The concept of fractal signals and some methods for their processing are given.

Chapter 2 provides the essential information from the fractional analysis theory. This information will further be used to describe fractional-order systems and to perform frequency domain analysis of circuits containing fractal elements (FE). This chapter introduces few examples of electrical and electrochemical engineering that exhibit fractional-order dynamics.

Chapter 3 introduces the concept of fractional elements (FEs) and gives their mathematical description. Several versions are given of known devices and electrical circuits of frequency-dependent fractional-order input impedances. The multilayer RC structure is substantiated as the base for creating FEs.

Chapters 4, 5, and 6 describe design, schematic, and fundamental techniques to implement FEs based on multilayer resistive-capacitive medium. Powerful capabilities to obtain the required parameters and characteristics of FEs by means of static and dynamic heterogeneous medium are shown.

Chapter 7 discloses physical effects that are used to create controlled resistors and capacitors. We can assume that the application of these effects to resistive and dielectric materials in multilayer resistive-capacitive structures will make it possible to create parametric and nonlinear FEs; and the latter will significantly expand the capabilities of these structures.

Chapter 8 provides an overview of FE applications for modeling, signal processing, designing control systems, hybrid computers, etc. Breadth of applications demands also a wide range of FE characteristics and parameters that can be implemented based on the multilayer RC medium. Therefore, the authors proposed a universal structural framework suitable for implementing FEs in various application areas. This structural framework contains seven alternating layers of resistive, dielectric, and conductive materials. The whole of these layers constitute a generalized virtual element.

Chapter 9 describes the technique of forming a system of partial differential equations for potential distribution in the resistive layers of the proposed virtual element. An example of FEs classification by resistive layers potential distribution is shown for the particular case of the fractal element with "resistor-insulator-resistor" layers structure.

Chapters 10, 11, and 12 describe in detail how to calculate the y-parameters of two-terminal and (in the general case) multi-terminal elements formed on the basis of RC multilayer medium which contains static and dynamic heterogeneities. These chapters are of particular importance for the practical implementation of FEs as long as this kind of problems had no satisfactory solutions till now. The authors used their proposed method of finite distributed elements to show that the external parameters of FEs can be calculated regardless of the complexity of the structure, the heterogeneous nature, and distribution in the RC medium. Several types of algorithms for calculating the *y*-parameters for different design implementations of FEs are proposed to the readers.

Practical exercises and test questions are given at the end of every chapter with the aim to consolidate the given material and to provide self-studying.

The authors suppose that this book sufficiently fulfills educational and innovative objectives in applying the ideas of fractal geometry and fractional analysis aimed to create fractal radio-electronics devices, communication systems, and for system identification and control of distributed and fractional-order processes.

Director of Kotel'nikov Institute S.A. Nikitov
of Radioengineering and Electronics
of Russian Academy of Sciences,
Doctor of Sciences in Physics
and Mathematics
Moscow, Russia

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