



# Fractional Calculus, Fractional Differential Equations and Applications

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## Abstract

In this paper, we describe two approaches to the definition of fractional derivatives. We investigate the accuracy of the analysis method for solving the fractional order problem. We also give some improvements for the proof of the existence and uniqueness of the solution in fractional differential equations. Treatment of a fractional derivative operator has been made associated with the extended Appell hypergeometric functions of two or three variables and Lauricella hypergeometric function of three variables.

## Subject Areas

Mathematical Analysis, Mathematical Algebra and Foundation of Mathematics

## Keywords

Fractional Derivative, Fractional Differentiation, Factorial for the Integer Numbers, Riemann-Liouville Fractional Derivative

## 1. Introduction

For compressible flows, in particular, there are additional degrees of fractional differential equations and treatment of a fractional derivative operator [1]. The latter can have very different characteristic amplitudes and scales in comparison with the vorticity field. Fractional-order systems are useful in studying the anomalous behavior of dynamical systems in physics, and electrochemistry. A particular difficulty of modeling such flows at high Reynolds (Re) numbers is the diversity of space and time scales that emerge as the flow develops. A particular difficulty of modeling such flows at high Reynolds (Re) numbers is the diversity of space and time scales that emerge as the flow develops fractional order models

# Functions Fractional Calculus Differintegral Equations

**B. Ross**



## **Functions Fractional Calculus Differintegral Equations:**

*Functional Fractional Calculus* Shantanu Das, 2011-06-01 When a new extraordinary and outstanding theory is stated it has to face criticism and skepticism because it is beyond the usual concept. The fractional calculus though not new was not discussed or developed for a long time particularly for lack of its application to real life problems. It is extraordinary because it does not deal with ordinary differential calculus. It is outstanding because it can now be applied to situations where existing theories fail to give satisfactory results. In this book not only mathematical abstractions are discussed in a lucid manner with physical mathematical and geometrical explanations but also several practical applications are given particularly for system identification, description and then efficient controls. The normal physical laws like transport theory, electrodynamics, equation of motions, elasticity, viscosity and several others are based on ordinary calculus. In this book these physical laws are generalized in fractional calculus contexts taking heterogeneity effect in transport background, the space having traps or islands, irregular distribution of charges, non ideal spring with mass connected to a point mass, ball material behaving with viscous as well as elastic properties, system relaxation with and without memory, physics of random delay in computer network and several others mapping the reality of nature closely. The concept of fractional and complex order differentiation and integration are elaborated mathematically, physically and geometrically with examples. The practical utility of local fractional differentiation for enhancing the character of singularity at phase transition or characterizing the irregularity, measure of response function is deliberated. Practical results of viscoelastic experiments, fractional order controls, experiments, design of fractional controller and practical circuit synthesis for fractional order elements are elaborated in this book. The book also maps theory of classical integer order differential equations to fractional calculus contexts and deals in details with conflicting and demanding initialization issues required in classical techniques. The book presents a modern approach to solve the solvable system of fractional and other differential equations, linear non linear without perturbation or transformations but by applying physical principle of action and opposite reaction giving approximately exact series solutions. Historically Sir Isaac Newton and Gottfried Wilhelm Leibniz independently discovered calculus in the middle of the 17th century. In recognition to this remarkable discovery J von Neumann remarked the calculus was the first achievement of modern mathematics and it is difficult to overestimate its importance. I think it defines more equivocally than anything else the inception of modern mathematical analysis which is logical development still constitutes the greatest technical advance in exact thinking. This XXI century has thus started to think exactly for advancement in science technology by growing application of fractional calculus and this century has started speaking the language which nature understands the best.

**Time-Fractional Differential Equations** Adam Kubica, Katarzyna Ryszewska, Masahiro Yamamoto, 2020-11-29 This book aims to establish a foundation for fractional derivatives and fractional differential equations. The theory of fractional derivatives enables considering any positive order of differentiation. The history of research in this field is very long with its

origins dating back to Leibniz. Since then many great mathematicians such as Abel have made contributions that cover not only theoretical aspects but also physical applications of fractional calculus. The fractional partial differential equations govern phenomena depending both on spatial and time variables and require more subtle treatments. Moreover, fractional partial differential equations are highly demanded model equations for solving real world problems such as the anomalous diffusion in heterogeneous media. The studies of fractional partial differential equations have continued to expand explosively. However, we observe that available mathematical theory for fractional partial differential equations is not still complete. In particular, operator theoretical approaches are indispensable for some generalized categories of solutions such as weak solutions, but feasible operator theoretic foundations for wide applications are not available in monographs. To make this monograph more readable, we are restricting it to a few fundamental types of time fractional partial differential equations, forgoing many other important and exciting topics such as stability for nonlinear problems. However, we believe that this book works well as an introduction to mathematical research in such vast fields.

[The Analysis of Fractional Differential Equations](#) Kai Diethelm, 2010-09-03 Fractional calculus was first developed by pure mathematicians in the middle of the 19th century. Some 100 years later, engineers and physicists have found applications for these concepts in their areas. However, there has traditionally been little interaction between these two communities. In particular, typical mathematical works provide extensive findings on aspects with comparatively little significance in applications, and the engineering literature often lacks mathematical detail and precision. This book bridges the gap between the two communities. It concentrates on the class of fractional derivatives most important in applications, the Caputo operators, and provides a self-contained thorough and mathematically rigorous study of their properties and of the corresponding differential equations. The text is a useful tool for mathematicians and researchers from the applied sciences alike. It can also be used as a basis for teaching graduate courses on fractional differential equations.

*Fractional Differential Equations* Igor Podlubny, 1998-10-27 This book is a landmark title in the continuous move from integer to non-integer in mathematics, from integer numbers to real numbers, from factorials to the gamma function, from integer order models to models of an arbitrary order. For historical reasons, the word fractional is used instead of the word arbitrary. This book is written for readers who are new to the fields of fractional derivatives and fractional order mathematical models and feel that they need them for developing more adequate mathematical models. In this book, not only applied scientists but also pure mathematicians will find fresh motivation for developing new methods and approaches in their fields of research. A reader will find in this book everything necessary for the initial study and immediate application of fractional derivatives, fractional differential equations, including several necessary special functions, basic theory of fractional differentiation, uniqueness and existence theorems, analytical, numerical methods of solution of fractional differential equations, and many inspiring examples of applications. A unique survey of many applications of fractional calculus. Presents basic theory. Includes a unified presentation of selected classical results which are

important for applications Provides many examples Contains a separate chapter of fractional order control systems which opens new perspectives in control theory The first systematic consideration of Caputo's fractional derivative in comparison with other selected approaches Includes tables of fractional derivatives which can be used for evaluation of all considered types of fractional derivatives      *Special Functions in Fractional Calculus and Engineering* Harendra Singh, H M Srivastava, R. K. Pandey, 2023-06-29 Special functions play a very important role in solving various families of ordinary and partial differential equations as well as their fractional order analogs which model real life situations Owing to the non local nature and memory effect fractional calculus is capable of modeling many situations which arise in engineering This book includes a collection of related topics associated with such equations and their relevance and significance in engineering *Special Functions in Fractional Calculus and Engineering* highlights the significance and applicability of special functions in solving fractional order differential equations with engineering applications This book focuses on the non local nature and memory effect of fractional calculus in modeling relevant to engineering science and covers a variety of important and useful methods using special functions for solving various types of fractional order models relevant to engineering science This book goes on to illustrate the applicability and usefulness of special functions by justifying their numerous and widespread occurrences in the solution of fractional order differential integral and integrodifferential equations This book holds a wide variety of interconnected fundamental and advanced topics with interdisciplinary applications that combine applied mathematics and engineering sciences which are useful to graduate students Ph D scholars researchers and educators interested in special functions fractional calculus mathematical modeling and engineering      *Introduction to Fractional Differential Equations* Constantin Milici, Gheorghe Drăgănescu, J. Tenreiro Machado, 2018-10-28 This book introduces a series of problems and methods insufficiently discussed in the field of Fractional Calculus a major emerging tool relevant to all areas of scientific inquiry The authors present examples based on symbolic computation written in Maple and Mathematica and address both mathematical and computational areas in the context of mathematical modeling and the generalization of classical integer order methods Distinct from most books the present volume fills the gap between mathematics and computer fields and the transition from integer to fractional order methods      *Theory and Applications of Fractional Differential Equations* A.A. Kilbas, H. M. Srivastava, J.J. Trujillo, 2006-02-16 This work aims to present in a systematic manner results including the existence and uniqueness of solutions for the Cauchy Type and Cauchy problems involving nonlinear ordinary fractional differential equations      **The Fractional Calculus Theory and Applications of Differentiation and Integration to Arbitrary Order**, 1974-09-05 In this book we study theoretical and practical aspects of computing methods for mathematical modelling of nonlinear systems A number of computing techniques are considered such as methods of operator approximation with any given accuracy operator interpolation techniques including a non Lagrange interpolation methods of system representation subject to constraints associated with concepts of causality memory and stationarity

methods of system representation with an accuracy that is the best within a given class of models methods of covariance matrix estimation methods for low rank matrix approximations hybrid methods based on a combination of iterative procedures and best operator approximation and methods for information compression and filtering under condition that a filter model should satisfy restrictions associated with causality and different types of memory As a result the book represents a blend of new methods in general computational analysis and specific but also generic techniques for study of systems theory and its particular branches such as optimal filtering and information compression Best operator approximation Non Lagrange interpolation Generic Karhunen Loeve transform Generalised low rank matrix approximation Optimal data compression Optimal nonlinear filtering

**Generalized Fractional Calculus and Applications** Virginia S Kiryakova, 1993-12-27 In this volume various applications are discussed in particular to the hyper Bessel differential operators and equations Dzrbashjan Gelfond Leontiev operators and Borel type transforms convolutions new representations of hypergeometric functions solutions to classes of differential and integral equations transmutation method and generalized integral transforms Some open problems are also posed This book is intended for graduate and post graduate students lecturers researchers and others working in applied mathematical analysis mathematical physics and related disciplines

**Special Functions and Analysis of Differential Equations** Praveen Agarwal, Ravi P Agarwal, Michael Ruzhansky, 2020-09-08 Differential Equations are very important tools in Mathematical Analysis They are widely found in mathematics itself and in its applications to statistics computing electrical circuit analysis dynamical systems economics biology and so on Recently there has been an increasing interest in and widely extended use of differential equations and systems of fractional order that is of arbitrary order as better models of phenomena in various physics engineering automatization biology and biomedicine chemistry earth science economics nature and so on Now new unified presentation and extensive development of special functions associated with fractional calculus are necessary tools being related to the theory of differentiation and integration of arbitrary order i e fractional calculus and to the fractional order or multi order differential and integral equations This book provides learners with the opportunity to develop an understanding of advancements of special functions and the skills needed to apply advanced mathematical techniques to solve complex differential equations and Partial Differential Equations PDEs Subject matters should be strongly related to special functions involving mathematical analysis and its numerous applications The main objective of this book is to highlight the importance of fundamental results and techniques of the theory of complex analysis for differential equations and PDEs and emphasizes articles devoted to the mathematical treatment of questions arising in physics chemistry biology and engineering particularly those that stress analytical aspects and novel problems and their solutions Specific topics include but are not limited to Partial differential equations Least squares on first order system Sequence and series in functional analysis Special functions related to fractional non integer order control systems and equations Various special functions related to generalized

fractional calculus Operational method in fractional calculus Functional analysis and operator theory Mathematical physics Applications of numerical analysis and applied mathematics Computational mathematics Mathematical modeling This book provides the recent developments in special functions and differential equations and publishes high quality peer reviewed book chapters in the area of nonlinear analysis ordinary differential equations partial differential equations and related applications

The Fractional Trigonometry Carl F. Lorenzo, Tom T. Hartley, 2016-11-14 Addresses the rapidly growing field of fractional calculus and provides simplified solutions for linear commensurate order fractional differential equations The Fractional Trigonometry With Applications to Fractional Differential Equations and Science is the result of the authors work in fractional calculus and more particularly in functions for the solutions of fractional differential equations which is fostered in the behavior of generalized exponential functions The authors discuss how fractional trigonometry plays a role analogous to the classical trigonometry for the fractional calculus by providing solutions to linear fractional differential equations The book begins with an introductory chapter that offers insight into the fundamentals of fractional calculus and topical coverage is then organized in two main parts Part One develops the definitions and theories of fractional exponentials and fractional trigonometry Part Two provides insight into various areas of potential application within the sciences The fractional exponential function via the fundamental fractional differential equation the generalized exponential function and R function relationships are discussed in addition to the fractional hyperbolicity the R1 fractional trigonometry the R2 fractional trigonometry and the R3 trigonometric functions The Fractional Trigonometry With Applications to Fractional Differential Equations and Science also Presents fractional trigonometry as a tool for scientists and engineers and discusses how to apply fractional order methods to the current toolbox of mathematical modelers Employs a mathematically clear presentation in an effort to make the topic broadly accessible Includes solutions to linear fractional differential equations and generously features graphical forms of functions to help readers visualize the presented concepts Provides effective and efficient methods to describe complex structures The Fractional Trigonometry With Applications to Fractional Differential Equations and Science is an ideal reference for academic researchers research engineers research scientists mathematicians physicists biologists and chemists who need to apply new fractional calculus methods to a variety of disciplines The book is also appropriate as a textbook for graduate and PhD level courses in fractional calculus Carl F Lorenzo is Distinguished Research Associate at the NASA Glenn Research Center in Cleveland Ohio His past positions include chief engineer of the Instrumentation and Controls Division and chief of the Advanced Controls Technology and Systems Dynamics branches at NASA He is internationally recognized for his work in the development and application of the fractional calculus and fractional trigonometry Tom T Hartley PhD is Emeritus Professor in the Department of Electrical and Computer Engineering at The University of Akron Dr Hartley is a recognized expert in fractional order systems and together with Carl Lorenzo has solved fundamental problems in the area including Riemann's complementary function initialization function problem He

received his PhD in Electrical Engineering from Vanderbilt University      *The Fundamentals of Fractional Calculus*  
 Dharmendra Kumar Singh, Mehmet Yavuz, 2025-09-23 Fractional calculus is one of the most important divisions of theoretical and applied mathematics This new book presents a wide variety of interesting technologies and practices used in fractional calculus providing detailed insight into recent developments and the latest research in the field of science engineering etc using fractional calculus The result of the teaching experiences of the editors and authors to engineering and science students the volume discusses fractional calculus via generalized functions and integral transforms of pathway type Laplace transformation of fractional integrals and derivatives estimating the order of derivation in a fractional differential equation a new class of integro differential equations with non singular differential operators various uses of the Caputo approach a gingerbread man discrete system etc The various applications of fractional calculus are shown with examples such as for creating and or solving epidemic models alcoholism models model for divorce dynamics and more Giving a rigorous and thorough analysis of various aspects of fractional calculus this volume helps scientific readers as well as researchers working in the area of fractional calculus to establish the key steps followed in the research methodology and concept development

**Fractional Calculus and Its Applications** B. Ross, 2006-11-15      *Fractional Differential Equations* Zhi-Zhong Sun, Guang-hua Gao, 2020-08-24 Starting with an introduction to fractional derivatives and numerical approximations this book presents finite difference methods for fractional differential equations including time fractional sub diffusion equations time fractional wave equations and space fractional differential equations among others Approximation methods for fractional derivatives are developed and approximate accuracies are analyzed in detail      *Introduction To The Fractional Calculus Of Variations* Delfim F M Torres, Agnieszka Barbara Malinowska, 2012-09-14 This invaluable book provides a broad introduction to the fascinating and beautiful subject of Fractional Calculus of Variations FCV In 1996 FVC evolved in order to better describe non conservative systems in mechanics The inclusion of non conservatism is extremely important from the point of view of applications Forces that do not store energy are always present in real systems They remove energy from the systems and as a consequence Noether s conservation laws cease to be valid However it is still possible to obtain the validity of Noether s principle using FCV The new theory provides a more realistic approach to physics allowing us to consider non conservative systems in a natural way The authors prove the necessary Euler Lagrange conditions and corresponding Noether theorems for several types of fractional variational problems with and without constraints using Lagrangian and Hamiltonian formalisms Sufficient optimality conditions are also obtained under convexity and Leitmann s direct method is discussed within the framework of FCV The book is self contained and unified in presentation It may be used as an advanced textbook by graduate students and ambitious undergraduates in mathematics and mechanics It provides an opportunity for an introduction to FCV for experienced researchers The explanations in the book are detailed in order to capture the interest of the curious reader and the book provides the necessary background material required to go further into the subject and



explore the rich research literature a *Fractional Calculus: Models And Numerical Methods* Dumitru Baleanu, Kai Diethelm, Enrico Scalas, Juan J Trujillo, 2012-01-27 The subject of fractional calculus and its applications that is convolution type pseudo differential operators including integrals and derivatives of any arbitrary real or complex order has gained considerable popularity and importance during the past three decades or so mainly due to its applications in diverse fields of science and engineering These operators have been used to model problems with anomalous dynamics however they also are an effective tool as filters and controllers and they can be applied to write complicated functions in terms of fractional integrals or derivatives of elementary functions and so on This book will give readers the possibility of finding very important mathematical tools for working with fractional models and solving fractional differential equations such as a generalization of Stirling numbers in the framework of fractional calculus and a set of efficient numerical methods Moreover we will introduce some applied topics in particular fractional variational methods which are used in physics engineering or economics We will also discuss the relationship between semi Markov continuous time random walks and the space time fractional diffusion equation which generalizes the usual theory relating random walks to the diffusion equation These methods can be applied in finance to model tick by tick log price fluctuations in insurance theory to study ruin as well as in macroeconomics as prototypical growth models All these topics are complementary to what is dealt with in existing books on fractional calculus and its applications This book was written with a trade off in mind between full mathematical rigor and the needs of readers coming from different applied areas of science and engineering In particular the numerical methods listed in the book are presented in a readily accessible way that immediately allows the readers to implement them on a computer in a programming language of their choice Numerical code is also provided

**Implicit Fractional Differential and Integral Equations** Saïd Abbas, Mouffak Benchohra, John R. Graef, Johnny Henderson, 2018-02-05 This book deals with the existence and stability of solutions to initial and boundary value problems for functional differential and integral equations and inclusions involving the Riemann Liouville Caputo and Hadamard fractional derivatives and integrals A wide variety of topics is covered in a mathematically rigorous manner making this work a valuable source of information for graduate students and researchers working with problems in fractional calculus Contents Preliminary Background Nonlinear Implicit Fractional Differential Equations Impulsive Nonlinear Implicit Fractional Differential Equations Boundary Value Problems for Nonlinear Implicit Fractional Differential Equations Boundary Value Problems for Impulsive NIFDE Integrable Solutions for Implicit Fractional Differential Equations Partial Hadamard Fractional Integral Equations and Inclusions Stability Results for Partial Hadamard Fractional Integral Equations and Inclusions Hadamard Stieltjes Fractional Integral Equations Ulam Stabilities for Random Hadamard Fractional Integral Equations

**Fractional Calculus: Models And Numerical Methods (Second Edition)** Juan J Trujillo, Enrico Scalas, Kai Diethelm, Dumitru Baleanu, 2016-09-15 This book will give readers the possibility of finding very important mathematical tools for working with fractional models and solving fractional differential equations

such as a generalization of Stirling numbers in the framework of fractional calculus and a set of efficient numerical methods. Moreover, we will introduce some applied topics in particular fractional variational methods which are used in physics, engineering, or economics. We will also discuss the relationship between semi-Markov continuous time random walks and the space-time fractional diffusion equation which generalizes the usual theory relating random walks to the diffusion equation. These methods can be applied in finance to model tick-by-tick log price fluctuations, in insurance theory to study ruin, as well as in macroeconomics as prototypical growth models. All these topics are complementary to what is dealt with in existing books on fractional calculus and its applications. This book will keep in mind the trade-off between full mathematical rigor and the needs of readers coming from different applied areas of science and engineering. In particular, the numerical methods listed in the book are presented in a readily accessible way that immediately allows the readers to implement them on a computer in a programming language of their choice. The second edition of the book has been expanded and now includes a discussion of additional newly developed numerical methods for fractional calculus and a chapter on the application of fractional calculus for modeling processes in the life sciences.

### **Numerical Methods for Fractional Differentiation**

Kolade M. Owolabi, Abdon Atangana, 2019-10-14. This book discusses numerical methods for solving partial differential and integral equations as well as ordinary differential and integral equations involving fractional differential and integral operators. Differential and integral operators presented in the book include those with exponential decay law known as Caputo-Fabrizio differential and integral operators, those with power law known as Riemann-Liouville fractional operators, and those for the generalized Mittag-Leffler function known as the Atangana-Baleanu fractional operators. The book reviews existing numerical schemes associated with fractional operators, including those with power law, while also highlighting new trends in numerical schemes for recently introduced differential and integral operators. In addition, the initial chapters address useful properties of each differential and integral fractional operator. Methods discussed in the book are subsequently used to solve problems arising in many fields of science, technology, and engineering, including epidemiology, chaos, solitons, fractals, diffusion, groundwater, and fluid mechanics. Given its scope, the book offers a valuable resource for graduate students of mathematics and engineering and researchers in virtually all fields of science, technology, and engineering, as well as an excellent addition to libraries.

### **Frontiers in Fractional Calculus** Sachin Bhalekar, 2018-03-21

This book brings together eleven topics on different aspects of fractional calculus in a single volume. It provides readers the basic knowledge of fractional calculus and introduces advanced topics and applications. The information in the book is presented in four parts: 1. Fractional Diffusion Equations: i) solutions of fractional diffusion equations using wavelet methods, ii) the maximum principle for time-fractional diffusion equations, iii) nonlinear sub-diffusion equations. 2. Mathematical Analysis: i) shifted Jacobi polynomials for solving and identifying coupled fractional delay differential equations, ii) the monotone iteration principle in the theory of Hadamard fractional delay differential equations, iii) dynamics of fractional order modified Bhalekar

Gejji System iv Grunwald Letnikov derivatives 3 Computational Techniques GPU computing of special mathematical functions used in fractional calculus 4 Reviews i the popular iterative method NIM ii fractional derivative with non singular kernels iii some open problems in fractional order nonlinear system This is a useful reference for researchers and graduate level mathematics students seeking knowledge about of fractional calculus and applied mathematics

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