# On the Numerical Solution of Singularly Perturbed Problems with Turning Points

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**Abstract**—The method of coordinate transformations is applied to the numerical solution of the first boundary value problem for weakly coupled second-order semilinear ordinary differential equations with a small parameter multiplying the highest order derivative. New estimates are obtained for the derivatives for an arbitrary set of boundary and internal turning points; these estimates allow one to efficiently construct coordinate transformations that eliminate the singularities of the solutions. A numerical algorithm is described, and results of calculations of certain model problems are presented for various types of singularities.

## INTRODUCTION

The development of methods and software for solving singularly perturbed problems, i.e., boundary value problems for equations with a small parameter $\varepsilon$ multiplying the highest order derivative, still remains topical. These problems arise when simulating fine physical and chemical processes in many important fields of science and technology. A distinctive feature of singularly perturbed problems is the presence of narrow regions (boundary and internal layers) where the derivatives attain large values (of the order of $\varepsilon^{-\kappa}$, $\kappa > 0$) for small $\varepsilon$. However, the solutions to these problems are mainly obtained both by analytical and numerical methods, whose error is estimated in terms of the derivatives of the unknown functions; therefore, in many cases, obtaining approximate solutions to singularly perturbed problems is a rather difficult task.

One of the trends in the investigation of singularly perturbed problems is the development of algorithms that allow one to obtain an approximate solution that converges to the exact solution uniformly with respect to $\varepsilon$. At present, there exist many methods that guarantee a uniform convergence for certain classes of problems. These are the analytical methods of the asymptotic expansion [1–9] and the numerical methods based on special schemes [10–13], on special coordinate transformations or special grids [14, 15], as well as on their combinations [16].

In this paper, we apply the method of special coordinate transformations that eliminate the singularities of the solutions to two-point boundary value problems for certain systems of second-order ordinary differential equations with a small parameter multiplying the highest order derivative.

The method of coordinate transformations is formulated for the numerical solution of the most general multidimensional singularly perturbed problems in a bounded physical domain $X^n \subset \mathbb{R}^n$. The key point in this method is the construction of new independent variables $\xi^1, \ldots, \xi^n$ obtained by the parameterization

$$\mathbf{x}(\xi, \varepsilon) : \Xi^n \longrightarrow X^n, \quad \xi = (\xi^1, \ldots, \xi^n), \quad \mathbf{x} = (x^1, \ldots, x^n),$$

where $\Xi^n$ is a standard bounded computational domain, for example, an $n$-dimensional cube. Here, the parameterization $\mathbf{x}(\xi, \varepsilon)$ is chosen so that the function $\mathbf{u}[\mathbf{x}(\xi, \varepsilon), \varepsilon]$, which is a composition of the solution $\mathbf{u}(\mathbf{x}, \varepsilon)$ to the singularly perturbed problem and the parameterization $\mathbf{x}(\xi, \varepsilon)$, has derivatives with respect to $\xi^1, \ldots, \xi^n$ to order $p \geq 1$ inclusive that are uniformly bounded with respect to $\varepsilon$ or at least admissible in magnitude. When such a coordinate transformation is found, a uniformly convergent solution can be obtained numerically by solving the transformed problem in the domain $\Xi^n$ on a uniform grid or in the physical domain $X^n$ on a nonuniform grid constructed by means of the parameterization $\mathbf{x}(\xi, \varepsilon)$ with the use of standard stable difference schemes.

In the general case, the required transformation $\mathbf{x}(\xi, \varepsilon)$ can be constructed by adaptive methods with the use of iterative solutions to special elliptic equations [17] or by a noninteractive process that employs one-

# Numerical Solution Of Singularly Perturbed Problems Using

**Guillaume Favre**

**Numerical Solution Of Singularly Perturbed Problems Using:**

Numerical Methods for Singularly Perturbed Differential Equations Hans-Görg Roos,Martin Stynes,Lutz Tobiska,2013-06-29 The analysis of singular perturbed differential equations began early in this century when approximate solutions were constructed from asymptotic ex pansions Preliminary attempts appear in the nineteenth century vD94 This technique has flourished since the mid 1960s Its principal ideas and methods are described in several textbooks Nevertheless asymptotic ex pansions may be impossible to construct or may fail to simplify the given problem then numerical approximations are often the only option The systematic study of numerical methods for singular perturbation problems started somewhat later in the 1970s While the research frontier has been steadily pushed back the exposition of new developments in the analysis of numerical methods has been neglected Perhaps the only example of a textbook that concentrates on this analysis is DMS80 which collects various results for ordinary differential equations but many methods and techniques that are relevant today especially for partial differential equa tions were developed after 1980 Thus contemporary researchers must comb the literature to acquaint themselves with earlier work Our purposes in writing this introductory book are twofold First we aim to present a structured account of recent ideas in the numerical analysis of singularly perturbed differential equations Second this important area has many open problems and we hope that our book will stimulate further investigations Our choice of topics is inevitably personal and reflects our own main interests    *Fitted Numerical Methods for Singular Perturbation Problems* John J. H. Miller,Eugene O'Riordan,G. I. Shishkin,2012 Since the first edition of this book the literature on fitted mesh methods for singularly perturbed problems has expanded significantly Over the intervening years fitted meshes have been shown to be effective for an extensive set of singularly perturbed partial differential equations In the revised version of this book the reader will find an introduction to the basic theory associated with fitted numerical methods for singularly perturbed differential equations Fitted mesh methods focus on the appropriate distribution of the mesh points for singularly perturbed problems The global errors in the numerical approximations are measured in the pointwise maximum norm The fitted mesh algorithm is particularly simple to implement in practice but the theory of why these numerical methods work is far from simple This book can be used as an introductory text to the theory underpinning fitted mesh methods    Difference Methods for Singular Perturbation Problems Grigory I. Shishkin,Lidia P. Shishkina,2008-09-22 Difference Methods for Singular Perturbation Problems focuses on the development of robust difference schemes for wide classes of boundary value problems It justifies the uniform convergence of these schemes and surveys the latest approaches important for further progress in numerical methods The first part of the book e    On the Numerical Solution of Singularly Perturbed Linear Two-Point Boundary-Value Problems B. S. Ng,W. H. Reid,INDIANA UNIV-PURDUE UNIV AT INDIANAPOLIS.,1985 This article presents an initial value technique based on the use of certain compound matrices for the numerical solution of linear two point boundary value problems involving unstable ordinary

differential equations of the singular perturbation type The authors demonstrate the effectiveness of the method via certain examples which exhibit internal as well as end point boundary layers **Numerical Methods for Singularly Perturbed Differential Equations** Hans-Görg Roos,Martin Stynes,Lutz Tobiska,2014-01-15 *Layer Resolving Grids and Transformations for Singular Perturbation Problems* Vladimir D. Liseikin,2018-11-05 No detailed description available for Layer Resolving Grids and Transformations for Singular Perturbation Problems **The Robust and Efficient Numerical Solution of Singularly Perturbed Boundary Value Problems Using Grid Adaptivity** Mark George Beckett,1998

Numerical Solution of Stiff and Singularly Perturbed Problems A. M. Nagy,2013 In recent years much attention has been given to the numerical solution of ODEs Of particular interest has been the solution of singularly perturbed and stiff problems These types of problems arise in various fields of science and engineering such as fluid mechanics physics chemistry mechanics chemical reactor theory convection diffusion processes optimal control and other branches of applied mathematics Singular perturbation problems depend on the presence of a small positive parameter which provides a multi scale character to the solution That is the solution varies very rapidly in some parts of the region of integration layers and varies slowly in other parts Stiffness is a property of the differential problem that makes slow and expensive the computation of the numerical solution using classical explicit methods In this work we present some numerical methods for solving IVPs and BVBs Moreover we give numerical solutions of Volterra integral and integro differential equations This book is high recommended to both postgraduate students and researchers in a wide variety of applications Layer-Adapted Meshes for Reaction-Convection-Diffusion Problems Torsten Linß,2009-11-21 This is a book on numerical methods for singular perturbation problems in part ular stationary reaction convection diffusion problems exhibiting layer behaviour More precisely it is devoted to the construction and analysis of layer adapted meshes underlying these numerical methods Numerical methods for singularly perturbed differential equations have been studied since the early 1970s and the research frontier has been constantly panding since A comprehensive exposition of the state of the art in the analysis of numerical methods for singular perturbation problems is 141 which was p lished in 2008 As that monograph covers a big variety of numerical methods it only contains a rather short introduction to layer adapted meshes while the present book is exclusively dedicated to that subject An early important contribution towards the optimisation of numerical methods by means of special meshes was made by N S Bakhvalov 18 in 1969 His paper spawned a lively discussion in the literature with a number of further meshes ing proposed and applied to various singular perturbation problems However in the mid 1980s this development stalled but was enlivened again by G I Shishkin s proposal of piecewise equidistant meshes in the early 1990s 121 150 Because of their very simple structure they are often much easier to analyse than other meshes although they give numerical approximations that are inferior to solutions on c peting meshes Shishkin meshes for numerous problems and numerical methods have been studied since and they are still very much in vogue Glimpses Of Kashmir S.K. Sopory,2004

The Book Contains The Proceedings Of A Seminar Relating To Kashmir And Attempts To Bring About A Synthesis Of Various Scientific Discipline As Well As Synthesis Of Science And Culture And Spritual Heritage Of Kashmir Divided Into Ii Parts Part I Covers Contribution Of Kashmiri Scientists And Part Ii Relates To Science Spirituality And Kashmir Shaivism

**Intelligent Computing Methodologies** De-Shuang Huang,M. Michael Gromiha,Kyungsook Han,Abir Hussain,2018-08-08 This book constitutes in conjunction with the two volume set LNCS 10954 and LNCS 10955 the refereed proceedings of the 14th International Conference on Intelligent Computing ICIC 2018 held in Wuhan China in August 2018 The 275 full papers and 72 short papers of the three proceedings volumes were carefully reviewed and selected from 632 submissions The papers are organized in topical sections such as Evolutionary Computation and Learning Neural Networks Pattern Recognition Image Processing Information Security Virtual Reality and Human Computer Interaction Business Intelligence and Multimedia Technology Biomedical Informatics Theory and Methods Swarm Intelligence and Optimization Natural Computing Quantum Computing Intelligent Computing in Computer Vision Fuzzy Theory and Algorithms Machine Learning Systems Biology Intelligent Systems and Applications for Bioengineering Evolutionary Optimization Foundations and Its Applications to Intelligent Data Analytics Swarm Evolutionary Algorithms for Scheduling and Combinatorial Optimization Swarm Intelligence and Applications in Combinatorial Qoptimization Advances in Metaheuristic Optimization Algorithm Advances in Image Processing and Pattern Techniques Bioinformatics **Single Perturbation Problems in Chemical Physics** John J. H. Miller,2009-09-09 The Matching Method for Asymptotic Solutions in Chemical PhysicsProblems by A M Il in L A Kalyakin and S I Maslennikov Singularly Perturbed Problems with Boundary and Interior Layers Theory and Application by V F Butuzov and A B Vasilieva Numerical Methods for Singularly Perturbed Boundary Value ProblemsModeling Diffusion Processes by V L Kolmogorov and G I Shishkin An important addition to the Advances in Chemical Physics series this volume makes available for the first time in English the workof leading Russian researchers in singular perturbation theory andits application Since boundary layers were first introduced byPrandtl early in this century rapid advances have been made in theanalytic and numerical investigation of these phenomena andnowhere have these advances been more notable than in the Russianschool of singular perturbation theory The three chapters in thisvolume treat various aspects of singular perturbations and theirnumerical solution and represent some of the best work done inthis area The first chapter The Matching Method for Asymptotic Solutionsin Chemical Physics Problems is concerned with the analysis ofsome singular perturbation problems that arise in chemicalkinetics In this chapter the matching method is applied to findasymptotic solutions to some dynamical systems of ordinarydifferential equations whose solutions have multiscale timedependence The second chapter Singularly Perturbed Problems with Boundaryand Interior Layers Theory and Application offers acomprehensive overview of the theory and application of asymptoticapproximations for many different kinds of problems in chemicalphysics governed by either ordinary or partial differentialequations with boundary and interior

layers The third chapter Numerical Methods for Singularly PerturbedBoundary Value Problems Modeling Diffusion Processes discussesthe numerical difficulties that arise in solving the problemsdescribed in the first two chapters and proposes rigorous criteriafor determining whether or not a numerical method is satisfactoryfor such problems Methods satisfying these criteria are thenconstructed and applied to obtain numerical solutions to a range ofsample problems Timely authoritative and invaluable to researchers in all areasof chemical physics Singular Perturbation Problems in ChemicalPhysics is an essential resource     Polynomials - Exploring Fundamental Mathematical Expressions Mudassir Shams,Bruno Carpentieri,2025-11-05 Polynomials Exploring Fundamental Mathematical Expressions offers an in depth overview of polynomial functions and structures showing their importance in both pure and applied mathematics The volume bridges fundamental concepts of theory with modern methods in symbolic computation approximation and mathematical modeling Intended for an audience of researchers engineers educators and advanced students this book highlights the critical role of polynomials as key tools for solving complex problems in various fields The volume offers readers a thorough and accessible resource in this critically important area of mathematics     Spline Solutions of Higher Order Boundary Value Problems Parcha Kalyani,2020-06-09 Doctoral Thesis Dissertation from the year 2014 in the subject Mathematics Applied Mathematics language English abstract Some of the problems of real world phenomena can be described by differential equations involving the ordinary or partial derivatives with some initial or boundary conditions To interpret the physical behavior of the problem it is necessary to know the solution of the differential equation Unfortunately it is not possible to solve some of the differential equations whether they are ordinary or partial with initial or boundary conditions through the analytical methods When we fail to find the solution of ordinary differential equation or partial differential equation with initial or boundary conditions through the analytical methods one can obtain the numerical solution of such problems through the numerical methods up to the desired degree of accuracy Of course these numerical methods can also be applied to find the numerical solution of a differential equation which can be solved analytically Several problems in natural sciences social sciences medicine business management engineering particle dynamics fluid mechanics elasticity heat transfer chemistry economics anthropology and finance can be transformed into boundary value problems using mathematical modeling A few problems in various fields of science and engineering yield linear and nonlinear boundary value problems of second order such as heat equation in thermal studies wave equation in communication etc Fifth order boundary value problems generally arise in mathematical modeling of viscoelastic flows The dynamo action in some stars may be modeled by sixth order boundary value problems The narrow convecting layers bounded by stable layers which are believed to surround A type stars may be modeled by sixth order boundary value problems which arise in astrophysics The seventh order boundary value problems generally arise in modeling induction motors with two rotor circuits Various phenomena such as convection flow in wind tunnels lee waves eddies etc can also be modeled by higher order boundary value problems     **Mathematical**

**Reviews** ,2005      **Analytical and Numerical Methods for Convection-dominated and Singularly Perturbed Problems** Lubin Vulkov,John James Henry Miller,2000 This volume is the Proceedings of the Workshop on Analytical and Computational Methods for Convection Dominated and Singularly Perturbed Problems which took place in Lozenetz Bulgaria 27 31 August 1998 The workshop attracted about 50 participants from 12 countries The volume includes 13 invited lectures and 19 contributed papers presented at the workshop and thus gives an overview of the latest developments in both the theory and applications of advanced numerical methods to problems having boundary and interior layers There was an emphasis on experiences from the numerical analysis of such problems and on theoretical developments The aim of the workshop was to provide an opportunity for scientists from the East and the West who develop robust methods for singularly perturbed and related problems and also who apply these methods to real life problems to discuss recent achievements in this area and to exchange ideas with a view of possible research co operation      **Robust Numerical Methods for Singularly Perturbed Differential Equations** Hans-Görg Roos,Martin Stynes,Lutz Tobiska,2008-09-17 This new edition incorporates new developments in numerical methods for singularly perturbed differential equations focusing on linear convection diffusion equations and on nonlinear flow problems that appear in computational fluid dynamics      **Invited Lectures Delivered at the Seventh International Colloquium on Differential Equations, August 18-23, 1996, Plovdiv, Bulgaria** ,1996      Applied Mechanics Reviews ,1985      **Novi Sad Journal of Mathematics** ,2003

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