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 ε 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 ε. 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 ε. 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 Ξ^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 ε 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 Ξ^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-

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