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ACCURATE NUMERICAL METHOD FOR SINGULARLY PERTURBED DIFFERENTIAL-DIFFERENCE EQUATIONS WITH MIXED SHIFTS

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Abstract. This paper is concerned with the numerical solution of the singularly perturbed differential-difference equations with small shifts called delay and advanced parameters. A fourth order finite difference method with a fitting factor is proposed for the solution of the singularly perturbed differential-difference equations with mixed shifts. The delay and advanced shifts are managed by Taylor series and an asymptotically equivalent singularly perturbed two-point boundary value problem is obtained. A fitting factor is introduced in the fourth order finite difference scheme for the problem which takes care of the small values of the perturbation parameter. This fitting factor is obtained from the asymptotic solution of singular perturbations. Thomas algorithm is used to solve the discrete system of the difference scheme. Convergence of the proposed method is analyzed. Maximum absolute errors in comparison with the several numerical experiments are tabulated to illustrate the proposed method.

1. Introduction

Singularly perturbed differential-difference equations (SPDDEs) arise very frequently in the mathematical modeling of real life situations in science and engineering [2],[6],[12]. Mathematically, any ordinary differential equation in which the highest derivative is multiplied by a small positive parameter and containing at least one delay/advance parameter is known as a singularly perturbed differential-difference equation. Lange and Miura [14]-[18] developed a series of

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papers to obtain an approximate solution of singularly perturbed differential-difference equations. Numerical analysis of SPDDE turning point problems was initiated by Kadalbajoo and Sharma. In a series of papers, see [7]-[11], they gave many robust numerical techniques for the solution of such type of problems. Kadalbajoo and Sharma [8] elucidate a numerical method to solve boundary value problems for SPDDEs. Kadalbajoo and Sharma [9] proposed a numerical method to solve a SPDDE of a mixed type with the case in which the solution of the problem exhibits rapid oscillations. Kadalbajoo and Sharma [10] described a numerical approach based on finite difference method to solve a mathematical model arising from a model of neuronal variability. Patidar and Sharma [20] combined fitted-operator methods with Micken's non-standard finite difference techniques for the numerical approximations of singularly perturbed linear delay differential equations. Kadalbajoo et al. [11] derived ϵ-uniformly convergent fitted methods for the solution of SPDDE. Kumar and Sharma [13] presented a numerical scheme based on B-spline collocation to approximate the solution of boundary value problems for SPDDEs with delay as well as advance. Amiraliyev and Cimen [5] derived a numerical method for singularly perturbed boundary value problem for a linear second order delay differential equation with a large delay in the reaction term. The authors constructed an exponentially fitted differential scheme on a uniform mesh accomplished by the method of integral identities with the use of exponential basis functions and interpolating quadrature rules with weight and the remainder term in the integral form. The paper is organized as follows:

In Section 2, the description of the problem is given. In Section 3, numerical scheme for the solution of the problem is derived and Section 4 deals with convergence analysis of the proposed scheme. To demonstrate the efficiency of the proposed method, numerical experiments are carried out for several test problems and the results are given in Section 5. Finally the conclusion is given in the last section.

2. Description of the problem

Consider a linear singularly perturbed differential-difference equation with mixed shifts of the form:

$$\varepsilon y''(x) + p(x)y'(x) + q(x)y(x-\delta) + r(x)y(x) + s(x)y(x+\eta) = f(x) \tag{2.1}$$

on (0, 1), under the boundary conditions

$$\begin{array}{ll} y(x) = \varphi(x) & \text{on} -\delta \le x \le 0, \\ y(\text{x}) = \gamma(x) & \text{on}\, 1 \le x \le 1+\eta, \end{array} \tag{2.2}$$

where ε is a small parameter, $0 < \varepsilon << 1$, $p(x), q(x), r(x), s(x), f(x), \varphi(x)$ and $\gamma(x)$ are smooth functions and $0 < \delta = o(\varepsilon)$, $0 < \eta = o(\varepsilon)$ are respectively the delay (negative shift) and the advance (positive shift) parameters. The solution of Eq. (2.1) and Eq. (2.6) exhibits: layer at the left end of the interval if $p(x) - \delta q(x) + \eta s(x) > 0$ and layer at the right end of the interval if $p(x) - \delta q(x) + \eta s(x) < 0$. If $p(x) \quad = 0$, then solution of the given problem may have oscillatory solution or two layers (one at each end) depending upon the cases whether $q(x) + r(x) + s(x)$ is positive or negative. Since the solution $y(x)$ of boundary value problem Eq. (2.1) & Eq. (2.6) is sufficiently differentiable, using Taylor series the terms $y(x-\delta)$ and $y(x+\eta)$ are expanded as [4]:

$$y(x-\delta) \approx y(x) - \delta y'(x) \tag{2.3}$$

$$y(x+\eta) \approx y(x) + \eta y'(x). \tag{2.4}$$

Using Eq. (2.3) and Eq. (2.4) in Eq. (2.1), we get

$$\varepsilon y''(x) + a(x)y'(x) + b(x)y(x) = f(x) \tag{2.5}$$

with boundary conditions

$$y(0) = \varphi(0) = \varphi_0 \tag{2.6}$$

$$y(1) = \gamma(1) = \gamma_1. \tag{2.7}$$

Here

$$a(x) = p(x) - \delta q(x) + \eta s(x)$$

$$b(x) = q(x) + r(x) + s(x)$$

. Eq. (2.5) is a second order singularly perturbed two point boundary value problem.

The zeroth order approximation to the solution [19] of (2.5) is

$$\lim_{h\to 0} y(ih) \approx y_0(0) + (\varphi(0) - y_0(0)\exp\{-a(0)i\rho\} \qquad \text{for } i = 0,1,2,...,N,$$

where $\rho = \frac{h}{\varepsilon}$ and y_0 represents the zeroth order approximate outer solution (i.e., the solution of the reduced problem).

3. Numerical Method

Consider the uniform grid ω_h=$\{x_i = ih \quad \text{for} \quad i = 0, 1, 2, \dots, N, h = 1/N\}$ on [0, 1]. At the grid point $x = x_i$, Eq.(2.5) becomes

$$\varepsilon y_i'' + a_i y_i' + b_i y_i = f_i. \tag{3.1}$$

We now consider higher order central difference formulae for y_i' and y_i'' as given below

$$y_i'' \cong \frac{y_{i-1} - 2y_i + y_{i+1}}{h^2} - \frac{h^2}{12} y_i^{(4)} + R_1 \tag{3.2}$$

$$y_i' = \frac{y_{i+1} - y_{i-1}}{2h} - \frac{h^2}{6} y_i''' + R_2, \tag{3.3}$$

where

$$R_1 = -\frac{2h^4 y^{(6)}(\xi)}{6!}$$

$$R_2 = -\frac{h^4 y^{(5)}(\eta)}{5!}$$

for $\xi, \eta \in [x_{i-1},\ x_{i+1}]$. Differentiating Eq.(2.5), we obtain y_i''', $y_i^{(4)}$ as

$$y_i''' = \left[-\frac{a_i}{\varepsilon} y_i'' - \frac{(a_i' + b_i)}{\varepsilon} y_i' - \frac{b_i'}{\varepsilon} y + \frac{f'}{\varepsilon}\right] \tag{3.4}$$

$$y_i^{(4)} = \left[\frac{a_i^2}{\varepsilon^2} - \frac{(2a_i' + b_i)}{\varepsilon}\right] y_i'' + \left[\frac{a_i\,(a_i' + b_i)}{\varepsilon^2} - \frac{(a_i'' + 2b_i')}{\varepsilon}\right] y_i' + \left[\frac{ab_i'}{\varepsilon^2} - \frac{b_i''}{\varepsilon}\right] y_i + \frac{1}{\varepsilon} f_i''. \tag{3.5}$$

Using Eq. (3.4) and Eq. (3.5) in Eq. (3.2) and Eq. (3.3), then substituting y_i' and y_i'' in Eq. 3.1, we get

$$\begin{aligned}&\varepsilon\left[A_1(i)\left(\tfrac{y_{i-1}-2y_i+y_{i+1}}{h^2}\right)+B_1(i)\tfrac{(y_{i+1}-y_{i-1})}{2h}-C_1(i)y_i-\tfrac{h^2}{12\varepsilon}f''{}_i\right]\\&+a_i\left[A_2(i)\left(\tfrac{y_{i-1}-2y_i+y_{i+1}}{h^2}\right)+B_2(i)\tfrac{(y_{i+1}-y_{i-1})}{2h}+C_2(i)y_i-\tfrac{h^2f'{}_i}{6\varepsilon}\right]+b_iy_i=f_i\end{aligned}$$

Here $A(i)=1-\frac{h^2{a_i}^2}{12\varepsilon^2}+\frac{h^2(2a'{}_i+b_i)}{12\varepsilon}$, $B(i)=\frac{h^2(a''{}_i+2b'{}_i)}{12\varepsilon}-\frac{h^2a_i(a'{}_i+b_i)}{12\varepsilon}$,

$C(i)=\frac{h^2b''{}_i}{12\varepsilon}-\frac{a_ib'{}_ih^2}{12\varepsilon^2}$, $A_2(i)=\frac{a_ih^2}{6\varepsilon}$, $B_2(i)=1+\frac{h^2}{6\varepsilon}(a'{}_i+b_i)$, $C_2(i)=\frac{h^2}{6\varepsilon}b'{}_i$.

Now introducing a fitting factor σ in the above finite difference scheme, we get

$$\begin{aligned}&\varepsilon\left[A_1(i)\left(\tfrac{y_{i-1}-2y_i+y_{i+1}}{h^2}\right)+B_1(i)\tfrac{(y_{i+1}-y_{i-1})}{2h}-C_1(i)y_i-\tfrac{h^2}{12\varepsilon}f''{}_i\right]\\&+a_i\left[A_2(i)\left(\tfrac{y_{i-1}-2y_i+y_{i+1}}{h^2}\right)+B_2(i)\tfrac{(y_{i+1}-y_{i-1})}{2h}+C_2(i)y_i-\tfrac{h^2f'{}_i}{6\varepsilon}\right]+b_iy_i=f_i.\end{aligned}\tag{3.6}$$

Multiplying the above equation by h, taking the limit as $h\to 0$ and using Lemma 3 in [3], we get the fitting factor as:

$$\sigma=\frac{a(0)}{2}\left(\frac{\coth\left(\frac{a(0)\rho}{2}\right)-\frac{\rho a^2(0)}{3}}{\left(\frac{1}{\rho}-\frac{\rho a^2(0)}{12}\right)}\right).\tag{3.7}$$

The tridiagonal system Eq.(3.6) is given by

$$E_iy_{i-1}-F_iy_i+G_iy_{i+1}=H_i,\quad i=1,2,\dots,N-1,\tag{3.8}$$

where

$$\begin{aligned}E_i=&\tfrac{\sigma\varepsilon}{h^2}-\tfrac{\sigma{a_i}^2}{12\varepsilon}+\tfrac{\sigma(2a'{}_i+b_i)}{12}+\tfrac{\sigma{a_i}^2}{6\varepsilon}-\tfrac{\sigma h}{24}(a''{}_i+2b'{}_i)+\tfrac{\sigma ha_i(a'{}_i+b_i)}{24\varepsilon}\\&-\tfrac{a_i}{2h}\left(1+\tfrac{h^2}{6\varepsilon}(a'{}_i+b_i)\right)\end{aligned}$$

$$F_i=\tfrac{2\sigma a_i^2}{12\varepsilon}-\tfrac{2\sigma\varepsilon}{h^2}-\tfrac{2\sigma(2a_i'+b_i)}{12}-\tfrac{2\sigma a_i^2}{6}+\tfrac{\sigma h^2b_i''}{12}-\tfrac{\sigma h^2a_ib_i'}{12\varepsilon}+\tfrac{h^2a_i^2b_i'}{6\varepsilon}+b_i$$

$$\begin{aligned}G_i=&\tfrac{\sigma\varepsilon}{h^2}-\tfrac{\sigma a_i^2}{12\varepsilon}+\tfrac{\sigma(2a_i'+b_i)}{12}+\tfrac{a_i^2}{6\varepsilon}+\tfrac{\sigma h}{24}(a_i''+2b_i')_-\tfrac{\sigma ha_i(a_i'+b_i)}{24\varepsilon}\\&+\tfrac{a_i}{2h}\left(1+\tfrac{h^2}{6\varepsilon}(a_i'+b_i)\right)\end{aligned}$$

$$H_i=\frac{\sigma\varepsilon h^2}{12\varepsilon}f_i''+\frac{a_ih^2}{6\varepsilon}f_i'+f_i.$$

Eq. (3.8) is solved by using Thomas algorithm [1].

4. CONVERGENCE ANALYSIS

The matrix-vector form of the tridiagonal system of Eq. (3.8) is

$$AY = C, \tag{4.1}$$

where $A = (m_{i\,j})$, $1 \le i, j \le N$-1 is a tridiagonal matrix of order N-1 , with

$$m_{ii+1} = \tfrac{\sigma\varepsilon}{h^2} - \tfrac{\sigma a_i^2}{12\varepsilon} + \tfrac{\sigma(2a_i'+b_i)}{12} + \tfrac{a_i^2}{6\varepsilon} + \tfrac{\sigma h}{24}(a_i'' + 2b_i')_{-}\tfrac{\sigma h a_i(a_i'+b_i)}{24\varepsilon} + \tfrac{a_i}{2h}\left(1 + \tfrac{h^2}{6\varepsilon}(a_i' + b_i)\right)$$

$$m_{ii} = \tfrac{2\sigma a_i^2}{12\varepsilon} - \tfrac{2\sigma\varepsilon}{h^2} - \tfrac{2\sigma(2a_i'+b_i)}{12} - \tfrac{2\sigma a_i^2}{6} + \tfrac{\sigma h^2 b_i''}{12} - \tfrac{\sigma h^2 a_i b_i'}{12\varepsilon} + \tfrac{h^2 a_i^2 b_i'}{6\varepsilon} + b_i$$

$$m_{ii-1} = \tfrac{\sigma\varepsilon}{h^2} - \tfrac{\sigma a_i^2}{12\varepsilon} + \tfrac{\sigma(2a_i'+b_i)}{12} + \tfrac{\sigma a_i^2}{6\varepsilon} - \tfrac{\sigma h}{24}(a_i'' + 2b_i') + \tfrac{\sigma h a_i(a_i'+b_i)}{24\varepsilon}$$
$$-\tfrac{a_i}{2h}\left(1 + \tfrac{h^2}{6\varepsilon}(a_i' + b_i)\right)$$

and $C = (d_i)$ is a column vector with $d_{\mathrm{i}} = -f_i h$ where i = 1,2,...,N-1 with local truncation error

$$\tau_i = \sigma\varepsilon\{\frac{y_{i+1} - y_i + y_{i-1}}{h^2} - \frac{h^2}{12}y_i^{4)} - y_i''\} + a(x)\{\left(\frac{y_{i+1} - y_{i-1}}{2h} - \frac{h^2}{6}y_i^{(3)}\right) - y_i'\}$$

$$|\tau_i| \le \max_{x_{i-1}\le x\le x_{i+1}}\left\{\frac{h^4 a(x)}{5!}\left|y^{(5)}(x)\right|\right\} + \max_{x_{i-1}\le x\le x_{i+1}}\left\{\frac{2h^4\sigma\varepsilon}{6!}\left|y^{(6)}(x)\right|\right\}$$

i.e.,

$$|\tau_i| \le O\left(h^4\right). \tag{4.2}$$

We have $Y = (y_0, y_1, y_2, ..., y_N)^t$. We also have

$$A\bar{Y} - T(h) = C, \tag{4.3}$$

where $\bar{Y} = (\bar{y}_0, \bar{y}_1, ..., \bar{y}_N)^t$ denotes the actual solution and $T(h) = (T_0(h), T_1(h), ..., T_N(h))^t$ is the local truncation error. From Eq. (4.1) and Eq. (4.3), we get $A\left(\bar{Y} - Y\right) = T(h)$,
Thus the error equation is

$$AE = T(h), \tag{4.4}$$

where $E = \bar{Y} - Y = (e_0, e_1, ..., e_N)^t$. Clearly, we have

$$S_i = \sum_{j=1}^{N-1} m_{ij} = -\tfrac{\sigma\varepsilon}{h^2} + \tfrac{\sigma a_i^2}{12\varepsilon} - \tfrac{\sigma(2a_i'+b_i)}{12} - \tfrac{a_i^2}{6\varepsilon} + \tfrac{a_i h^2 b_i''}{12}{}_{-}\tfrac{\sigma h^2 a_i b_i^1}{12\varepsilon} + \tfrac{a_i^2 h^2 b_i^1}{6\varepsilon} + b_i + \tfrac{\sigma h a_i''}{24\varepsilon}$$
$$+\tfrac{\sigma h b_i'}{12} - \tfrac{\sigma h a_i a_i'}{24\varepsilon} - \tfrac{\sigma h a_i b_i}{24\varepsilon} + \tfrac{a_i}{2h}\left(1 + \tfrac{h^2}{6\varepsilon}(a_i' + b_i)\right),\ for\ \ i = 1$$

$$S_i = \sum_{j=1}^{N-1} m_{ij} = b_i - \tfrac{\sigma h^2 b_i''}{12} - \tfrac{\sigma a_i b_i' h^2}{12\varepsilon} + \tfrac{a_i h^2 b_i'}{6\varepsilon}$$
$$= b_i + O(h^2) = B_{i_0}, \text{for } i = 2, 3, ..., N - 2$$

$$S_i = \sum_{j=1}^{N-1} m_{ij} = -\tfrac{\sigma\varepsilon}{h^2} + \tfrac{\sigma a_i^2}{12\varepsilon} - \tfrac{\sigma(2a_i'+b_i)}{12} - \tfrac{a_i^2}{6\varepsilon} - \tfrac{\sigma h(a_i''+2b_i')}{24} + \tfrac{\sigma h a_i(a_i'+b_i)}{24\varepsilon}$$
$$-\tfrac{a_i}{2h}\left(1 + \tfrac{h^2}{6\varepsilon}(a_i' + b_i)\right) + \tfrac{a_i h^2 b_i''}{12} - \tfrac{\sigma h^2 a_i b_i^1}{12\varepsilon} + \tfrac{a_i^2 h^2 b_i^1}{6\varepsilon} + b_i\, for\ i = N - 1.$$

We can choose h so that the matrix A is irreducible and monotone. It follows that A^{-1} exists and its elements are non negative. Hence, using Eq. (4.4), we get $E = A^{-1}T(h)$ and

$$\|E\| \leq \|A^{-1}\|\|T(h)\|. \tag{4.5}$$

Also from the theory of matrices we have

$$\sum_{i=1}^{N-1} \bar{m}_{k,i}\, S_i = 1 \ , \ \ k = 1\,(1)\, N\text{-}1 \ , \tag{4.6}$$

where $\bar{m}_{k,i}$ is (k,i) element of the matrix A^{-1} for some i_0 between 1 and $N-1$. Therefore

$$\sum_{i=1}^{N-1} \bar{m}_{k,i} \leq \frac{1}{\min\limits_{1\leq i\leq N-1} S_i} = \frac{1}{B_{i_0}} \leq \frac{1}{|B_{i_0}|}. \tag{4.7}$$

We define $\|A^{-1}\| = \sum\limits_{i=1}^{N-1} |\bar{m}_{k,i}|$ and $\|T(h)\| = \sum\limits_{i=1}^{N-1} |T_i(h)|$. From Eq. (4.2), Eq. (4.5) and Eq. (4.7), we get

$$e_j = \sum_{i=1}^{N-1} \bar{m}_{k.i} T_i(h), \ \ j = 1(1)N-1$$

which implies

$$e_j \leq \frac{O\left(h^4\right)}{|B_{i_0}|}, \quad j = 1(1)N-1,$$

where $B_{i_0} = b_i$. Therefore,

$$\|E\| = O\left(h^4\right)$$

i.e., the proposed method reduces to a fourth order convergent on uniform mesh.

5. Numerical examples

To demonstrate the method computationally, we have considered three numerical examples. The numerical results are compared with the other method [10]. We have traced the graphs of the computed solution of the problem for different values of δ and η.

$$\epsilon y^{''} + p(x)y^{'} + q(x)y(x-\delta) + r(x)y(x) + s(x)y(x+\eta) = f(x)$$

under the boundary conditions

$$y(x) = \phi(x) \ on \ -\delta \leq x \leq 0$$

$$y(x) = \gamma(x) \ on \ 1 \leq x \leq 1+\eta$$

is

$$y_\epsilon(x) = c_1 e^{m_1(x)} + c_2 e^{m_2(x)} + \frac{f}{c},$$

where

$$c_1 = \frac{[-f + \gamma c + e^{m_2}(f - \phi c)]}{(e^{m_1} - e^{m_2})c}$$

$$c_2 = \frac{[-f + \gamma c + e^{m_1}(-f + \phi c)]}{(e^{m_1} - e^{m_2})c}$$

$$m_1 = \frac{-(p - q\delta + s\eta) + \sqrt{(p - q\delta + s\eta)^2 - 4\epsilon c}}{2\epsilon}$$
$$m_2 = \frac{-(p - q\delta + s\eta) - \sqrt{(p - q\delta + s\eta)^2 - 4\epsilon c}}{2\epsilon},$$

where $c = (q + r + s)$.

Example 1. Consider the model boundary value problem of the type given by equations (1)-(2) having the boundary layer at the left-end

$$\epsilon y^{''} + y^{'} - 2y(x - \delta) - 5y + y(x + \eta) = 0$$

with boundary conditions $y(x) = 1,\ -\delta \leq x \leq 0, \quad y(x) = 1,\ 1 \leq x \leq 1 + \eta$
The maximum absolute errors are given in Tables 1 and 2 for different values of the delay and advanced parameters with perturbation parameter. The effect of the small parameters on the boundary layer solutions is shown in Figures 1 and 2.

Example 2. Consider the non homogeneous boundary value problem of the type given by equations (1)-(2) having the boundary layer at the left end

$$\epsilon y^{''} + y^{'} - 2y(x - \delta) + y - y(x + \eta) = -1$$

with boundary conditions $y(x) = 1,\ -\delta \leq x \leq 0, \quad y(x) = 1,\ 1 \leq x \leq 1 + \eta$
The maximum absolute errors are given in Table 3 for different values of with the delay and advance parameter values . The effect of the small parameters on the boundary layer solutions is shown in Figures 3 and 4.

Example 3. Consider the model boundary value problem of the type given by equations (1)-(2) having the boundary layer at the right end

$$\epsilon y^{''} - y^{'} - 2y(x - \delta) + y - y(x + \eta) = 0$$

with boundary conditions $y(x) = 1,\ -\delta \leq x \leq 0, \quad y(x) = -1,\ 1 \leq x \leq 1 + \eta$
The maximum absolute errors are given in Table 4 with $\epsilon = 0.1$ for different values of the delay and advance parameters. The effect of the small parameters on the boundary layer solutions is shown in Figures 5 and 6.

6. Discussions and Conclusions

A fourth order finite difference method with fitting factor has been presented for solving singularly perturbed differential-difference equations with delay as well as advance parameters. A fitting factor is assigned to this scheme to control rapid behaviour in the boundary layer due to the perturbation parameter when it takes small values. To demonstrate the method computationally, two examples with left-end and one with right-end boundary layer have been solved for different values of the delay, advance and perturbation parameters. Matlab is used for the numerical results and graphs. Maximum absolute errors in the solution of the problems are presented in tables. To support the method, numerical results taken by the proposed scheme are compared with the results of Kadalbajoo and Sharma [10]. It is observed that the present method approximates the exact solution very well for which other classical finite difference methods fail to give good results. The effect of the delay and advance parameters on the solutions has also been investigated and shown in graphs. From the numerical results, we noticed that the method gives good results even for $h > \varepsilon$. From the graphs, we observed that, when the solution of the boundary-value problem exhibits layer behaviour on the left side, the effect of delay or advance on the solution in the boundary layer region is negligible while in the outer region, it is considerable i.e., the increase in the delay increases the width of outer region while the increase in the advance decreases the width of outer region(Figures 1-4). When the solution of the boundary-value problem exhibits layer behaviour on the right side, the changes in delay or advance affect the solution in boundary layer region as well as outer region. The thickness of the layer increases as the size of the delay increases while it decreases as the size of the advance increases (Figures 5-6).

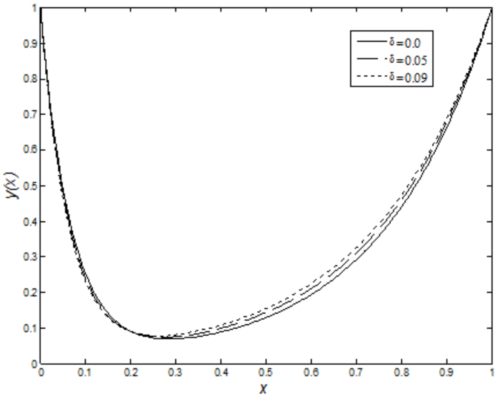

Figure 1. Numerical solution of Example 1 for different values of δ with ϵ=0.1, η=0.05.

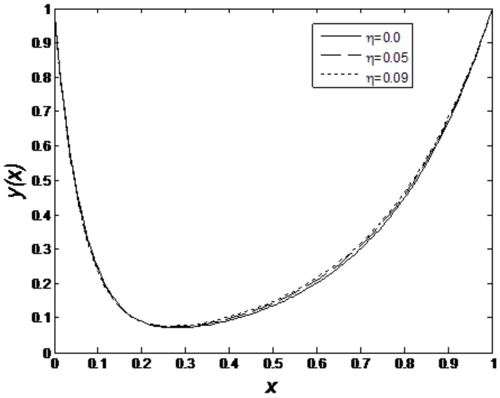

Figure 2. Numerical solution of Example 1 for different values of η with ϵ=0.1, δ=0.05.

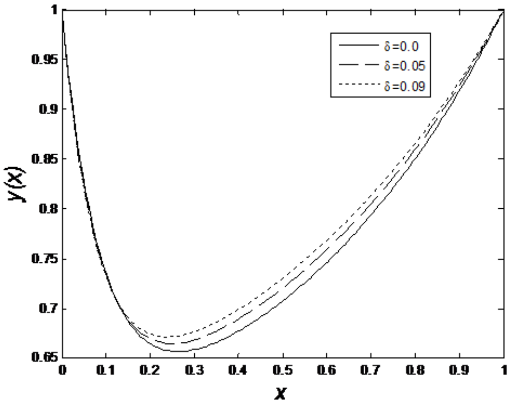

Figure 3. Numerical solution of Example 2 for different values of δ with ϵ=0.1, η=0.05.

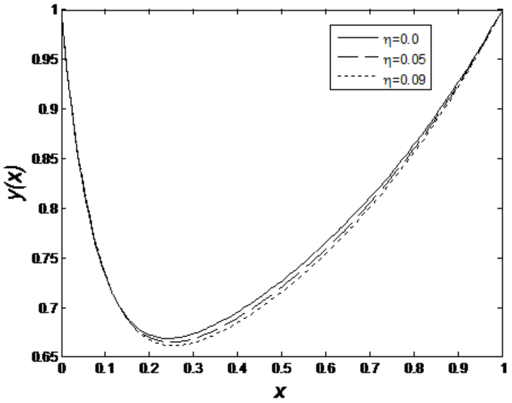

Figure 4. Numerical solution of Example 2 for different values of η with ϵ=0.1, δ=0.05.

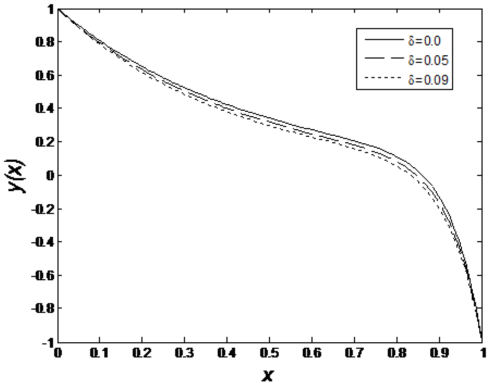

Figure 5. Numerical solution of Example 3 for different values of η with ϵ=0.1, η=0.05.

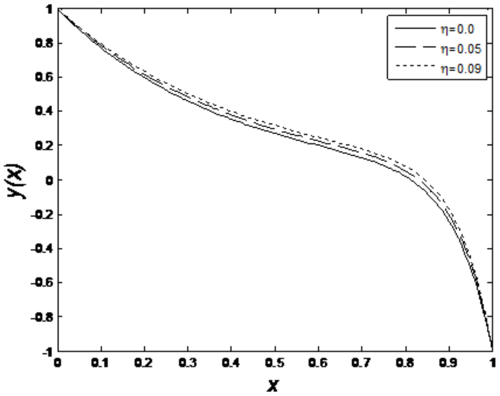

Figure 6. Numerical solution of Example 3 for different values of η with ϵ=0.1, δ=0.05.

Table 1. The maximum absolute errors in solution of Example 1

$\epsilon \downarrow$	$N = 8$	$N = 16$	$N = 32$	$N = 64$	$N = 128$	$N = 256$
			$\delta = \eta = 0.5\,\epsilon$			
10^{-1}	0.0033038	0.0002201	$1.29e-005$	$7.98e-007$	$4.96e-008$	$3.10e-009$
10^{-2}	0.0235839	0.0076541	0.0031533	0.0009899	$5.76e-005$	$3.42e-006$
10^{-3}	0.0399002	0.0228969	0.0114511	0.0048135	0.0011596	0.0028588
10^{-4}	0.0418088	0.0250830	0.0137409	0.0071056	0.0035127	0.0016458
10^{-5}	0.0420041	0.0253101	0.0139842	0.0073554	0.0037635	0.0018932
10^{-6}	0.0420237	0.0253329	0.0140087	0.0073808	0.0037892	0.0019190
			Results in [10]			
10^{-1}	0.1201156	0.0711396	0.0448298	0.0269461	0.0151609	0.0077503
10^{-2}	0.1872710	0.1069782	0.0590411	0.3079689	0.0156796	0.0079907
10^{-3}	0.2042972	0.1191502	0.0687923	0.0365523	0.0189384	0.0096330
10^{-4}	0.2061414	0.1204841	0.0698994	0.0372137	0.0193277	0.0098423
10^{-5}	0.2063274	0.1206188	0.0700116	0.0372808	0.0136732	0.0098636
10^{-6}	0.2063460	0.1206323	0.0700229	0.0372876	0.0193712	0.0098657

Table 2. The maximum absolute errors in solution of Example 1 with $\epsilon = 0.1$.

	$N = 8$	$N = 32$	$N = 128$	$N = 512$
$\delta \downarrow$		$\eta = 0.5\,\epsilon$		
0.00	0.00265280	$1.0220e-005$	$3.9258e-008$	$1.5344e-010$
0.05	0.00330379	$1.2961e-005$	$4.9696e-008$	$1.9390e-010$
0.09	0.003858959	$1.5323e-005$	$5.8654e-008$	$2.2897e-010$
$\eta \downarrow$		$\delta = 0.5\,\epsilon$		
0.00	0.00297213	$1.1559e-005$	$4.4365e-008$	$1.7319e-010$
0.05	0.00330379	$1.2961e-005$	$4.9696e-008$	$1.9390e-010$
0.09	0.00357767	$1.4124e-005$	$5.4113e-008$	$2.1112e-010$
$\delta \downarrow$		$\eta = 0.5\,\epsilon$(Results in [10])		
0.00	0.09190267	0.03453494	0.01164358	0.00300463
0.05	0.10233615	0.03823132	0.01295871	0.00335137
0.09	0.11018870	0.04110846	0.01400144	0.00362925
$\eta \downarrow$		$\delta = 0.5\,\epsilon$		
0.00	0.09720079	0.03640446	0.01229476	0.00317786
0.05	0.10233615	0.03823132	0.01295871	0.00335137
0.09	0.10632014	0.03965833	0.01348348	0.00349050

Table 3. The maximum absolute errors in solution of Example 2

$\epsilon \downarrow$	$N = 8$	$N = 16$	$N = 32$	$N = 64$	$N = 128$	$N = 256$
			$\delta = \eta = 0.5\epsilon$			
10^{-1}	0.0004362	$2.64e-005$	$1.58e-006$	$9.99e-008$	$6.22e-009$	$3.89e-010$
10^{-2}	0.0059028	0.0016684	0.0030736	0.0001274	$7.60e-006$	$4.51e-007$
10^{-3}	0.0075977	0.0040202	0.0019920	0.0009022	0.00030729	0.00031863
10^{-4}	0.0007726	0.0041663	0.0021546	0.0010890	0.00054083	0.00026222
10^{-5}	0.0007738	0.0041800	0.0021689	0.0011038	0.00055620	0.00027856
10^{-6}	0.0077398	0.0041813	0.0021703	0.0011052	0.00055765	0.00028002
			Results in [10]			
10^{-1}	0.0857969	0.0512956	0.0320213	0.0192472	0.0109835	0.0055359
10^{-2}	0.1337650	0.0764130	0.0421722	0.0219977	0.0111997	0.0057076
10^{-3}	0.1459266	0.0851073	0.0491373	0.0261088	0.0135274	0.0068807
10^{-4}	0.1472439	0.0860601	0.0499281	0.0265812	0.0138055	0.0070302
10^{-5}	0.1473767	0.0861563	0.0500083	0.0266292	0.0138338	0.0070454
10^{-6}	0.1473900	0.0861659	0.0500163	0.0266340	0.0138366	0.0070469

Table 4. The maximum absolute errors in solution of Example 3 with $\epsilon = 0.1$.

	$N = 8$	$N = 32$	$N = 128$	$N = 512$
$\delta \downarrow$		$\eta = 0.5\,\epsilon$		
0.00	0.002425427	$8.4802e-006$	$3.3166e-008$	$1.2946e-010$
0.05	0.001907515	$6.7239e-006$	$2.6104e-008$	$1.0189e-010$
0.09	0.001543162	$5.4589e-006$	$2.1118e-008$	$8.2514e-011$
$\eta \downarrow$		$\delta = 0.5\,\epsilon$		
0.00	0.001458758	$5.1627e-006$	$1.9978e-008$	$7.8025e-011$
0.05	0.001907515	$6.7239e-006$	$2.6104e-008$	$1.0189e-010$
0.09	0.002316112	$8.1139e-006$	$3.1667e-008$	$1.2364e-010$
$\delta \downarrow$		$\eta = 0.5\,\epsilon$(Results in [10])		
0.00	0.09930002	0.03685072	0.01331683	0.00342882
0.05	0.09997296	0.03218424	0.01167102	0.00299572
0.09	0.10044578	0.02850398	0.01038902	0.00266379
$\eta \downarrow$		$\delta = 0.5\,\epsilon$		
0.00	0.10055269	0.02759534	0.01007834	0.00258299
0.05	0.09997296	0.03218424	0.01167102	0.00299572
0.09	0.09944067	0.03591410	0.01297367	0.00334044

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