

Research Article

Numerical Solution of Dispersive Optical Solitons with Schrödinger-Hirota Equation by Improved Adomian Decomposition Method

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In this paper, we present new numerical results for the dispersive optical soliton solutions of the nonlinear Schrödinger-Hirota equation. The spatio-temporal dispersion term is included, in addition to group velocity dispersion Kerr law of nonlinearity are studied. A general recursive numerical scheme for the equation is devised via the Improved Adomian Decomposition Method (IADM) and further sought for some analytical results for validation. The scheme is shown to be efficient and possessed high level of accuracy as demonstrated.

1. Introduction

Nonlinear Schrodinger equations (NLSE) play a significant role in the fiber optics, optical soliton, prorogation of pulses in metamaterials and network engineering applications among others [1, 2]. Thus, different forms of NLSE exist and serve for a variety of purposes mostly in communication and networking engineering including, for example, the transcontinental and trans-oceanic data transfer requiring phase modulation [3] and beyond; see [4–16] for different mathematical studies on these equations. Furthermore, due to their immense application, many analytical methods and few numerical methods have been proposed in the past decades. Such methods include the Backlund transformation method [17], Hirota's direct method [18, 19], tanh-sech method [20, 21], extended tanh method [22, 23], sine-cosine method [24], and homogeneous balance method [25].

However, we will propose in this paper a numerical method for solving a class of NLSE called the nonlinear Schrodinger-Hirota equation. The method will heavily depend on the Improved Adomian Decomposition Method (IADM) [26–31]. The IADM is an efficient numerical method for functional and integral solutions based on the Adomian

decomposition method [32]. Further, a recent analytical study on the nonlinear Schrodinger-Hirota equation will be sought for to validate the proposed scheme. This form of solution is being reported for the first time in this paper.

2. Governing Equation

The nonlinear Schrodinger equation used in modeling propagation of solitons through optical fibers with Third-Order Dispersion (TOD) is given by

$$iu_t + \frac{1}{2}u_{xx} + |u|^2 u = -i\lambda u_{xxx},$$
 (1)

where u = u(x, t) is a complex-valued function of x (space) and t (time); λ is the coefficient of TOD. The first term on the left hand side is the linear temporal evolution, the second term is the group velocity dispersion term, and the third term accounts for Kerr law nonlinearity. Also when the group velocity is low, the TOD is justified.

We now introduced the Lie symmetry concept to be able to study (1). With q = q(x, t), let

$$q = u - 3i\lambda \left[u_x + 2u \int_{-\infty}^{x} \left| u(\xi) \right|^2 d\xi, \qquad (2)$$

which transforms (1) to

$$iq_{t} + \frac{1}{2}q_{xx} + |q|^{2}q + i\lambda\left(q_{xxx} + 6|q|^{2}q_{x}\right) = 0.$$
 (3)

In (3), higher order terms are neglected [11, 33, 34] with Kerr law nonlinearity that models transmission of dispersive optical solitons through nonlinear fibres. We express (3) with general coefficients as

$$iq_{t} + aq_{xx} + c|q|^{2}q + i(\gamma q_{xxx} + \sigma |q|^{2}q_{x}) = 0, \quad (4)$$

where physically σ represents nonlinear dispersion. Further, (4) happens to be ill-posed due to the group velocity dispersion term. However, with the addition of the spatiotemporal dispersion (STD) term, (4) possesses a well-posedness [35, 36] given by

$$iq_{t} + aq_{xx} + bq_{xt} + c|q|^{2} q + i(\gamma q_{xxx} + \sigma |q|^{2} q_{x}) = 0, \quad (5)$$

where the coefficient *b* represents STD. Finally, in presence of perturbation terms (5) becomes [37–39]

$$iq_{t} + aq_{xx} + bq_{xt} + c |q|^{2} q + i \left(\gamma q_{xxx+\sigma} |q|^{2} q_{x}\right)$$

$$= i\alpha q_{x} + i\lambda \left(|q|^{2} q\right)_{x} + i\nu \left(|q|^{2}\right)_{x} q.$$
(6)

However, we consider an analytical 1-soliton solution of (6) as special case presented by Al Qarni et al. [40] for the numerical simulation sake in Section 4 given by

$$q(x,t) = A \operatorname{sech} \left[B(x - vt) \right] e^{i(-k_l x + \omega_l t + \theta)},$$
(7)

where *k* is the frequencies of the solitons, ω is the wave number, θ is the phase velocity, and *A* and *B* are the amplitude and width *B* given, respectively, by

$$A = \sqrt{\frac{2\left(\omega + ak - \omega kb + ak^2 + \gamma k^3\right)}{a - b\nu\omega - 3\gamma k}},$$
(8)

$$B = \sqrt{\frac{2\left(\omega + ak - \omega kb + ak^2 + \gamma k^3\right)}{c + \sigma k - \lambda k}}.$$
(9)

The constraint conditions, for the existence of bright solitons from (7)-(9), are as follows:

$$(a - bv\omega - 3\gamma k) \left(2 \left(\omega + ak - \omega kb + ak^2 + \gamma k^3 \right) \right) > 0, \quad (10)$$

$$(c + \sigma k - \lambda k) \left(2 \left(\omega + ak - \omega kb + ak^2 + \gamma k^3 \right) \right) > 0.$$
(11)

3. Numerical Method

In [26–31], authors introduced the IADM to convert a special case of the complex-valued system into a real-valued system by splitting q(x, t) as

$$q(x,t) = u_1 + iu_2,$$
 (12)

where $(u_k, k = 1, 2)$ are real functions. By substituting equation (12) into (6) we obtain the following system:

$$u_{1t} + au_{2xx} + bu_{2xt} + c \left(u_1^2 + u_2^2\right) u_2 + \gamma u_{1xxx} + \sigma \left(u_1^2 + u_2^2\right) u_{1x} = \alpha u_{1x} + \lambda \left(\left(u_1^2 + u_2^2\right) u_1\right)_x$$
(13)
$$- v \left(u_{1x}^2 + u_{2x}^2\right) u_1, u_{2t} - au_{1xx} - bu_{1xt} - c \left(u_1^2 + u_2^2\right) u_1 + \gamma u_{2xxx} + \sigma \left(u_1^2 + u_2^2\right) u_{2x} = \alpha u_{2x} + \lambda \left(\left(u_1^2 + u_2^2\right) u_2\right)_x$$
(14)
$$+ v \left(u_{1x}^2 + u_{2x}^2\right) u_2,$$

where

$$u_{1}(x,0) = [q(x,0)]_{R},$$

$$u_{2}(x,0) = [q(x,0)]_{I}.$$
(15)

The decomposition method [32] decomposes the solution into infinite sums of components defined by

$$u_{1}(x,t) = \sum_{n=0}^{\infty} u_{1n}(x,t), \qquad (16)$$

$$u_{2}(x,t) = \sum_{n=0}^{\infty} u_{2n}(x,t), \qquad (17)$$

where the components $u_{1n}, u_{2n}, n \ge 0$ will be determined recursively. In an operator form with $L_t = \partial/\partial t$, (14) and (15) become

$$L_{t} (u_{1} + bu_{2x}) + au_{2xx} + c (u_{1}^{2} + u_{2}^{2})u_{2} + \gamma u_{1xxx} + \sigma (u_{1}^{2} + u_{2}^{2})u_{1x} = \alpha u_{1x} + \lambda ((u_{1}^{2} + u_{2}^{2})u_{1})_{x}$$
(18)
$$- v (u_{1x}^{2} + u_{2x}^{2})u_{1}, L_{t} (u_{2} - b_{1}u_{1x}) - au_{1xx} - c (u_{1}^{2} + u_{2}^{2})u_{1} + \gamma u_{2xxx} + \sigma (u_{1}^{2} + u_{2}^{2})u_{2x} = \alpha u_{2x} + \lambda ((u_{1}^{2} + u_{2}^{2})u_{2})_{x}$$
(19)
$$+ v (u_{1x}^{2} + u_{2x}^{2})u_{2}.$$

Taking the inverse operator L_t^{-1} to both sides of (18) and (19) gives

$$u_{1}(x,t) = u_{1}(x,0) - b \left(u_{2x}(x,t) - u_{2x}(x,0) \right) - L_{t}^{-1} a u_{2xx} - L_{t}^{-1} \gamma u_{1xxx} + L_{t}^{-1} \alpha u_{1x}$$
(20)
+ $L_{t}^{-1} A_{1},$
$$u_{2}(x,t) = u_{2}(x,0) + b \left(u_{1x}(x,t) - u_{1x}(x,0) \right) + L_{t}^{-1} a u_{1xx} - L_{t}^{-1} \gamma u_{2xxx} + L_{t}^{-1} \alpha u_{2x}$$
(21)
+ $L_{t}^{-1} A_{2}.$

Assuming that the nonlinear terms in (20) and (21) are represented by the series,

$$A_{1} = -c \left(u_{1}^{2} + u_{2}^{2}\right)u_{2} - \sigma \left(u_{1}^{2} + u_{2}^{2}\right)u_{1x} + \lambda \left(\left(u_{1}^{2} + u_{2}^{2}\right)u_{1}\right)_{x} + v \left(u_{1x}^{2} + u_{2x}^{2}\right)u_{1}, \\ A_{2} = c \left(u_{1}^{2} + u_{2}^{2}\right)u_{1} - \sigma \left(u_{1}^{2} + u_{2}^{2}\right)u_{2x} + \lambda \left(\left(u_{1}^{2} + u_{2}^{2}\right)u_{2}\right)_{x} + v \left(u_{1x}^{2} + u_{2x}^{2}\right)u_{2},$$

$$(23)$$

 $A_{1n}, \ldots, A_{2n}, \ldots$ are the so-called Adomian polynomials that can be constructed for all forms of nonlinearity according to specific algorithms set by Adomian [32]. Substituting the nonlinear terms into (22) and (23) and the solution from (16) and (17) into (20) and (21) gives

$$\sum_{n=0}^{\infty} u_{1n}(x,t)$$

$$= u_{1}(x,0) - b\sum_{n=0}^{\infty} (u_{2n}(x,t))_{x} + b(u_{2n}(x,0))_{x}$$

$$- L_{t}^{-1}a\sum_{n=0}^{\infty} (u_{2n}(x,t))_{xx} \qquad (24)$$

$$- L_{t}^{-1}\gamma\sum_{n=0}^{\infty} (u_{1n}(x,t))_{xxx} + L_{t}^{-1}\alpha\sum_{n=0}^{\infty} (u_{1n}(x,t))_{x}$$

$$+ L_{t}^{-1}\sum_{n=0}^{\infty} A_{1n},$$

$$\sum_{n=0}^{\infty} u_{2n}(x,t)$$

$$= u_{2}(x,0) + b\sum_{n=0}^{\infty} (u_{1n}(x,t))_{x} - b(u_{1n}(x,0))_{x}$$

$$+ L_{t}^{-1}a\sum_{n=0}^{\infty} (u_{1n}(x,t))_{xx} \qquad (25)$$

$$-L_{t}^{-1}\gamma\sum_{n=0}^{\infty}\left(u_{2n}(x,t)\right)_{xxx}+L_{t}^{-1}\alpha\sum_{n=0}^{\infty}\left(u_{2n}(x,t)\right)_{x}$$
$$+L_{t}^{-1}\sum_{n=0}^{\infty}A_{2n}.$$

Following the decomposition analysis, the following recursive relations are introduced:

$$u_{1,0}(x,t) = u_1(x,0) + b(u_2(x,0))_x, \qquad (26)$$

$$u_{2,0}(x,t) = u_2(x,0) - b(u_1(x,0))_x, \qquad (27)$$

$$u_{1,k+1}(x,t) = -b (u_{2,k}(x,t))_{x} - L_{t}^{-1} a (u_{2,k}(x,t))_{xx}$$

$$- L_{t}^{-1} \gamma (u_{1,k}(x,t))_{xxx}$$
(28)
$$+ L_{t}^{-1} \alpha (u_{1,k}(x,t))_{x} + L_{t}^{-1} A_{1,m},$$

$$u_{2,k+1}(x,t) = b (u_{1,k}(x,t))_{x} + L_{t}^{-1} a (u_{1,k}(x,t))_{xx}$$

$$+ L_{t}^{-1} \gamma (u_{2n}(x,t))_{xxx}$$
(29)
$$+ L_{t}^{-1} \alpha (u_{2n}(x,t))_{x} + L_{t}^{-1} A_{2,m}.$$

Thus, we determine u_1 and u_2 as follows:

$$u_1 = u_{1,0} + u_{1,1} + u_{1,2} + \cdots$$

$$u_2 = u_{2,0} + u_{2,1} + u_{2,2} + \cdots$$
(30)

and the overall approximate solution for (6) is obtained by substituting the above into (12) coupled to (26)-(29) to get

$$q(x,t) = u_{1,0} + u_{1,1} + u_{1,2} + \cdots + i (u_{2,0} + u_{2,1} + u_{2,2} + \cdots).$$
(31)

4. Numerical Results

In this section, we consider three different cases for the Schrödinger-Hirota equation with spatiotemporal dispersion given in (6) to illustrate the application of the IADM scheme we presented in the above section. We also consider the bright soliton solution given in (7)-(11) for numerical simulation with the following fixed parameters: $\omega = 1$, $k_1 = k = 0.1$, $\theta = 0, c = 1, a = 0.5$. We also represent the graphs for absolute value for each of exact solution q_e and approximate solution q_a .

Example 1. We consider Schrödinger-Hirota equation with spatiotemporal dispersion equation (6) with b = 0.0 and the following three special cases.

Case 1. Let
$$\gamma = 0.0$$
.
Case 2. Let $\gamma = 0.6$.
Case 3. Let $\gamma = 1.0$.

The results and the profiles of this example are presented in Table 1 and Figure 1.

Example 2. We consider Schrödinger-Hirota equation with spatiotemporal dispersion equation (6) with b = 0.1 and the following three special cases.

Case 1. Let
$$\gamma = 0.0$$
.
Case 2. Let $\gamma = 0.6$.
Case 3. Let $\gamma = 1.0$.

The result and the profiles of this example are presented in Table 2 and Figure 2.



FIGURE 1: Comparison of the exact and approximate solution for Example 1 for $-20 \le x \le 20$.

| <i>b</i> = 0 | | | |
|----------------|---|--|--|
| $\gamma = 0$ | $\gamma = 0.6$ | $\gamma = 1$ | |
| 0.0 | 0.0 | 0.0 | |
| 0.000010261373 | 0.00003209069 | 0.00006378300 | |
| 0.000021764973 | 0.00006266170 | 0.00012599913 | |
| 0.000034488427 | 0.00009173715 | 0.00018667002 | |
| 0.000048407918 | 0.00011934200 | 0.00024581792 | |
| 0.000063498224 | 0.00014550173 | 0.00030346539 | |
| | $\gamma = 0$ 0.0 0.000010261373 0.000021764973 0.000034488427 0.000048407918 0.000063498224 | b = 0 $\gamma = 0$ 0.0 0.000010261373 0.000003209069 0.000021764973 0.000034488427 0.00009173715 0.000048407918 0.00011934200 0.000014550173 | |

TABLE 1: The absolute error for Example 1 when x = 20.

| TABLE 2: The absolute error for Example 2 when $x = 20$ |
|---|
|---|

| t | b = 0.1 | | | |
|-----|--------------------------|-------------------------|-------------------------|--|
| | $\gamma = 0$ | $\gamma = 0.6$ | $\gamma = 1$ | |
| 0.0 | 5.47003×10 ⁻⁷ | 7.5968×10 ⁻⁷ | 8.7637×10 ⁻⁷ | |
| 0.1 | 0.000013623790 | 0.00003154594 | 0.00006498593 | |
| 0.2 | 0.000028096531 | 0.00006216823 | 0.00012912151 | |
| 0.3 | 0.000043940472 | 0.00009113126 | 0.00019155154 | |
| 0.4 | 0.000061129371 | 0.00011845995 | 0.00025229764 | |
| 0.5 | 0.000079635465 | 0.00014417984 | 0.00031138194 | |



FIGURE 2: Comparison of the exact and approximate solution for Example 2 for $-20 \le x \le 20$.

| TABLE 3: | The absolute | error for | Example 3 | when $x = 20$ |
|----------|--------------|-----------|-----------|---------------|
| | | | | |

| t | <i>b</i> = 0.6 | | | |
|-----|----------------|----------------|---------------|--|
| | $\gamma = 0$ | $\gamma = 0.6$ | $\gamma = 1$ | |
| 0.0 | 0.00014373490 | 0.00017576127 | 0.00019563219 | |
| 0.1 | 0.00014417980 | 0.00011583001 | 0.00009275551 | |
| 0.2 | 0.00014701256 | 0.00005817085 | 0.00000758921 | |
| 0.3 | 0.00015221500 | 0.00000366844 | 0.00010541473 | |
| 0.4 | 0.00015976708 | 0.00004859351 | 0.00020073458 | |
| 0.5 | 0.00016964674 | 0.00009833252 | 0.00029356299 | |



FIGURE 3: Comparison of the exact and approximate solution for Example 3 for $-20 \le x \le 20$.

Example 3. We consider Schrödinger-Hirota equation with spatiotemporal dispersion equation (6) with b = 0.6 and the following three special cases.

Case 1. Let $\gamma = 0.0$.

Case 2. Let $\gamma = 0.6$.

Case 3. Let $\gamma = 1.0$.

The result and the profiles of this example are presented in Table 3 and Figure 3.

5. Conclusion

In this work, an Improved Adomian Decomposition Method (IADM) has been proposed to solve the nonlinear Schrodinger-Hirota equation in presence of several Hamiltonian type perturbation terms. The obtained results possess high precision and converged to the exact solution with less computational efforts. It was noticed that a high accuracy of results is obtained when is the coefficient of 3OD $\gamma = 0$ and within the range $0 > \gamma$, b < 1 (*b* is the coefficient of spatio-temporal dispersion term) as commented also in [40]. It is also clear from Figures 1–3 that the complete correspondence of the two solutions is indeed remarkable. Thus, the IADM is an efficient method for nonlinear Schrodinger equational efforts as compared to other numerical methods. This topic is still open for further

researches for different values of parameters and other types of soliton solutions.

Data Availability

All the data used for the numerical simulations and comparison purpose have been reported in the tables included and visualized in the graphical illustrations and nothing is left.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Journal of **Function Spaces**



International Journal of **Differential Equations**



Abstract and Applied Analysis



Discrete Dynamics in Nature and Society



Advances in Mathematical Physics