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Optical Soliton Perturbation with Dispersive Concatenation Model: Semi–Inverse Variation

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Abstract. The current paper recovers a bright 1-soliton solution to the perturbed dispersive concatenation model, with Kerr's law of self-phase modulation, with the aid of the semi-inverse variational principle. The perturbation terms are of Hamiltonian type and appear with arbitrary intensity. The parameter constraints that naturally emerge from the analysis are presented.

Keywords: solitons, dispersive concatenation, stationary integral
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1. Introduction

The concatenation model was first proposed exactly a decade ago, in 2014, when three well–known equations from nonlinear fiber optics were conjoined. They are the nonlinear Schrödinger's equation (NLSE), Lakshmanan–Porsezian-Daniel (LPD), and Sasa–Satsuma equation. This model gained a lot of popularity with its several features. The Painleve analysis was addressed, the soliton solutions were identified, its conservation laws were located, and the gap solitons for the model were presented. Subsequently, the model was addressed with polarization–mode dispersion, and several of its features were also reported in various works. The following year, a similar model was proposed, referred to as the dispersive concatenation model. This is the combination of the Schrödinger–Hirota equation (SHE), LPD, and fifth–order NLSE. The dispersive effects for this model stem from the SHE and the fifth–order NLSE components. This second form of concatenation model was also extensively studied, and several of its features became known [1–5].

It is now time to turn the page. The dispersive concatenation model will be addressed in this paper in the presence of perturbation terms. These are all of Hamiltonian type and appear with arbitrary intensity. This perturbed version of the dispersive concatenation model comes with linear chromatic dispersion (CD) and Kerr law of self–phase modulation, which will be addressed in the paper. The perturbation terms are all of Hamiltonian type and come with arbitrary intensity. A bright 1–soliton solutions will be recovered for the model by the aid of semi–inverse variational principle (SVP). The soliton solution that will be identified is not exact but is analytical. The parameter constraints for the existence of the solitons naturally emerge from the mathematical analysis and will be enumerated. The rest of the paper exhibits the details of the model and its soliton solution derivation.

2. Governing model

The dispersive concatenation model with Kerr's law of SPM is structured as [4–7]:

$$\begin{aligned} & iq_t + aq_{xx} + b|q|^2 q - i\delta_1\left[\sigma_1 q_{xxx} + \sigma_2 |q|^2 q_x\right] \\ & +\delta_2\left[\begin{array}{l}\sigma_3 q_{xxxx} + \sigma_4 |q|^2 q_{xx} + \sigma_5 |q|^4 q + \\ \sigma_6 |q_x|^2 q + \sigma_7 q_x^2 q^* + \sigma_8 q^* q^2\end{array}\right] \\ & -i\delta_3\left[\begin{array}{l}\sigma_9 q_{xxxxx} + \sigma_{10} |q|^2 q_{xxx} + \sigma_{11} |q|^4 q_x + \sigma_{12} q q_x q_{xx}^* \\ +\sigma_{13} q^* q_x q_{xx} + \sigma_{14} q q_x^* q_{xx} + \sigma_{15} q_x^2 q_x^*\end{array}\right] \\ & = i\left[\lambda\left(|q|^{2m} q\right)_x + \theta_1\left(|q|^{2m}\right)_x q + \theta_2 |q|^{2m} q_x\right]. \end{aligned} \tag{1}$$

Here, $q(x,t)$ represents a complex-valued function that describes the wave amplitude. In this context, x and t represent the spatial and temporal coordinates, respectively. The parameters a and b correspond to CD and SPM, respectively. The parameter $i=\sqrt{-1}$ is the imaginary unit. The coefficients δ_1, δ_2, and δ_3 are the non–zero parameters and represent the coefficients of SHE, the LPD model and the fifth–order NLSE, respectively. The perturbation terms are from self–shortening effects and self–frequency shifts, represented by the λ and θ_j for $j=1,2$ respectively. Finally, the parameter m in the perturbation terms represents the arbitrary intensity factor.

The 1–soliton solution to (1) for $\lambda=\theta_j=0$, for $j=1,2$ is given by:

$$q(x,t) = A\,\mathrm{sech}\left[B(x-vt)\right]e^{-i(-\kappa x+\omega t+\theta)}. \tag{2}$$

In (2), A represents the amplitude of the solitons, while B gives its inverse width, and v is the speed of the soliton. The phase component is represented by the κ - the soliton wavenumber, while ω and θ give the frequency and phase constant, respectively.

It must be noted that the derivation of the soliton solution for the perturbed concatenation model with Kerr law and power-law of SPM by the implementation of SPM has been reported [6, 7]. To seek soliton solutions to the dispersive concatenation model given by (1) for nonzero λ and θ_j its structural format is taken to be:

$$q(x,t) = g(x-vt)e^{i\phi(x,t)}, \tag{3}$$

from which the phase factor is:

$$\phi(x,t) = -\kappa x + \omega t + \theta, \tag{4}$$

where g represents the amplitude portion of the bright soliton. By substituting (3) and (4) into (1) and splitting into real and imaginary parts, one obtains for the real part as:

$$
\begin{aligned}
&\left(-\omega-\alpha\kappa^{2}+\delta_{1}\sigma_{1}\kappa^{3}+\delta_{2}\sigma_{3}\kappa^{4}-\delta_{3}\sigma_{9}\kappa^{5}\right)g \\
&-\alpha-3\delta_{1}\sigma_{1}\kappa-6\delta_{2}\sigma_{3}\kappa^{2}+10\delta_{3}\sigma_{9}\kappa^{3}g''+\delta_{2}\sigma_{3}-5\delta_{3}\sigma_{9}\kappa g^{(iv)} \\
&+\begin{pmatrix} b-\delta_{1}\sigma_{2}-\delta_{2}\sigma_{4}\kappa^{2}+\delta_{2}\sigma_{6}\kappa^{2}-\delta_{2}\sigma_{7}\kappa^{2}-\delta_{2}\sigma_{8}\kappa^{2}+\delta_{3}\sigma_{10}\kappa^{3} \\ +\delta_{3}\sigma_{12}\kappa^{3}+\delta_{3}\sigma_{13}\kappa^{3}-\delta_{3}\sigma_{14}\kappa^{3}-\delta_{3}\sigma_{15}\kappa^{3} \end{pmatrix} g^{3} \\
&+\left(\delta_{2}\sigma_{4}+\delta_{2}\sigma_{8}-3\delta_{3}\sigma_{10}\kappa-\delta_{3}\sigma_{12}\kappa-\delta_{3}\sigma_{13}\kappa+\delta_{3}\sigma_{14}\kappa\right)g''g^{2} \\
&+\left(\delta_{2}\sigma_{6}+\delta_{2}\sigma_{7}+2\delta_{3}\sigma_{12}\kappa-2\delta_{3}\sigma_{13}\kappa-2\delta_{3}\sigma_{14}\kappa-\delta_{3}\sigma_{15}\kappa\right)\left(g'\right)^{2}g \\
&+\left(\delta_{2}\sigma_{5}-\delta_{3}\sigma_{11}\kappa\right)g^{(v)}-\kappa\left(\lambda+\theta_{2}\right)g^{2m+1}=0.
\end{aligned} \tag{5}
$$

The imaginary part leads to the following:

$$
\begin{aligned}
&-vg_{t}+\left(-2\alpha\kappa+3\delta_{1}\sigma_{1}\kappa^{2}+4\delta_{2}\sigma_{3}\kappa^{3}-5\delta_{3}\sigma_{9}\kappa^{4}\right)g' \\
&+\left(-\delta_{1}\sigma_{1}-4\delta_{2}\sigma_{3}\kappa+10\delta_{3}\sigma_{9}\kappa^{2}\right)g''' \\
&-\delta_{3}\sigma_{9}g^{(v)} \\
&+\begin{pmatrix} -\delta_{1}\sigma_{2}-\delta_{2}\sigma_{4}\kappa-2\delta_{2}\sigma_{7}\kappa+2\delta_{2}\sigma_{8}\kappa+3\delta_{3}\sigma_{10}\kappa^{2} \\ -\delta_{3}\sigma_{12}\kappa^{2}+3\delta_{3}\sigma_{13}\kappa^{2}-\delta_{3}\sigma_{14}\kappa^{2}-\delta_{3}\sigma_{15}\kappa^{2} \end{pmatrix} g'g^{2} \\
&-\left(2m+1\right)\lambda+2m\theta_{1}+\theta_{2}g'g^{2m} \\
&-\delta_{3}\sigma_{11}g'g^{4}-\left(\delta_{3}\sigma_{12}+\delta_{3}\sigma_{13}+\delta_{3}\sigma_{14}\right)g''g'g \\
&-\delta_{3}\sigma_{15}(g')^{3}-\delta_{3}\sigma_{10}g'''g^{2}=0.
\end{aligned} \tag{6}
$$

The notations $g'=dg/ds$, $g''=d^{2}g/ds^{2}$, $g'''=d^{3}g/ds^{3}$, $g^{(iv)}=d^{4}g/ds^{4}$ and $g^{(v)}=d^{5}g/ds^{5}$ are adopted. The constraint conditions that emerge from (6) are given as:

$$\sigma_{9}=\sigma_{10}=\sigma_{11}=\sigma_{15}=0, \tag{7}$$

$$\sigma_{13}=-\sigma_{12}-\sigma_{14}, \tag{8}$$

$$\delta_{1}\sigma_{1}=-4\delta_{2}\sigma_{3}\kappa, \tag{9}$$

$$\delta_{1}\sigma_{2}=-\delta_{2}\sigma_{4}\kappa-2\delta_{2}\sigma_{7}\kappa+2\delta_{2}\sigma_{8}\kappa+4\delta_{3}\sigma_{13}\kappa^{2}, \tag{10}$$

and

$$\delta_{1}\sigma_{1}=-2\delta_{2}\sigma_{4}\kappa-2\delta_{2}\sigma_{7}\kappa+2\delta_{2}\sigma_{8}\kappa+4\delta_{3}\sigma_{13}\kappa^{2}. \tag{11}$$

Given the imaginary component in (6) and the condition given by equations (7)–(11), the soliton speed is given by:

$$v=-2\alpha\kappa+2\delta_{1}\sigma_{1}\kappa^{2}. \tag{12}$$

Given the outcome of the σ_{9}, σ_{10}, σ_{11}, and σ_{15} terms, equation (1) reduces to the following:

$$
\begin{aligned}
&iq_{t}+aq_{xx}+b|q|^{2}q-i\delta_{1}\left[\sigma_{1}q_{xxx}+\sigma_{2}|q|^{2}q_{x}\right] \\
&+\delta_{2}\left[\sigma_{3}q_{xxxx}+\sigma_{4}|q|^{2}q_{xx}+\sigma_{5}|q|^{4}q+\sigma_{6}|q_{x}|^{2}q+\sigma_{7}q_{x}^{2}q^{*}+\sigma_{8}q_{xx}^{*}q^{2}\right] \\
&-i\delta_{3}\left[\sigma_{12}qq_{x}q_{xx}^{*}+\sigma_{13}q^{*}q_{x}q_{xx}+\sigma_{14}qq_{x}^{*}q_{xx}\right] \\
&=i\left[\lambda\left(|q|^{2m}q\right)_{x}+\theta_{1}\left(|q|^{2m}\right)_{x}q+\theta_{2}|q|^{2m}q_{x}\right].
\end{aligned} \tag{13}
$$

While following the same conditions, the real components of the equation reduce to the following:

$$
\begin{aligned}
&\left(-\omega-\alpha\kappa^2+\delta_1\sigma_1\kappa^3+\delta_2\sigma_3\kappa^4\right)g-\alpha-3\delta_1\sigma_1\kappa-6\delta_2\sigma_3\kappa^2 g''+\delta_2\sigma_3 g^{(iv)}\\
&+\begin{pmatrix} b-\delta_1\sigma_2-\delta_2\sigma_4\kappa^2+\delta_2\sigma_6\kappa^2-\delta_2\sigma_7\kappa^2-\delta_2\sigma_8\kappa^2\\ +\delta_3\sigma_{12}\kappa^3+\delta_3\sigma_{13}\kappa^3-\delta_3\sigma_{14}\kappa^3 \end{pmatrix}g^3\\
&+\left(\delta_2\sigma_4+\delta_2\sigma_8-\delta_3\sigma_{12}\kappa-\delta_3\sigma_{13}\kappa+\delta_3\sigma_{14}\kappa\right)g''g^2\\
&+\left(\delta_2\sigma_6+\delta_2\sigma_7+2\delta_3\sigma_{12}\kappa-2\delta_3\sigma_{13}\kappa-2\delta_3\sigma_{14}\kappa\right)\left(g'\right)^2 g\\
&+\left(\delta_2\sigma_5\right)g^5+\kappa\left(-\lambda-\theta_2\right)g^{2m+1}=0.
\end{aligned}
\tag{14}
$$

The following notations are now adopted for simplicity:

$$P_1=-\omega-\alpha\kappa^2+\delta_1\sigma_1\kappa^3+\delta_2\sigma_3\kappa^4, \tag{15}$$

$$P_2=\alpha-3\delta_1\sigma_1\kappa-6\delta_2\sigma_3\kappa^2, \tag{16}$$

$$P_3=\delta_2\sigma_3, \tag{17}$$

$$
\begin{aligned}
P_4=&\, b-\delta_1\sigma_2-\delta_2\sigma_4\kappa^2+\delta_2\sigma_6\kappa^2-\delta_2\sigma_7\kappa^2\\
&-\delta_2\sigma_8\kappa^2+\delta_3\sigma_{12}\kappa^3+\delta_3\sigma_{13}\kappa^3-\delta_3\sigma_{14}\kappa^3,
\end{aligned}
\tag{18}
$$

$$P_5=\delta_2\sigma_5, \tag{19}$$

and

$$P_6=-\kappa\left(\lambda+\theta_2\right). \tag{20}$$

A couple of additional parameter constraints that emerge for integrability of the real part equation (14) are:

$$\delta_2\sigma_4+\delta_2\sigma_8-\delta_3\sigma_{12}\kappa-\delta_3\sigma_{13}\kappa+\delta_3\sigma_{14}\kappa=0, \tag{21}$$

and

$$\delta_2\sigma_6+\delta_2\sigma_7+2\delta_3\sigma_{12}\kappa-2\delta_3\sigma_{13}\kappa-2\delta_3\sigma_{14}\kappa=0. \tag{22}$$

3. Semi-inverse variation

Multiplying (14) by g' given the previous conditions of (21) and (22) and then integrating will lead to:

$$6P_1g^2-6P_2\left(g'\right)^2+6P_3\left\{2g'''g'-\left(g''\right)^2\right\}+3P_4g^4+2P_5g^6+\frac{6P_6g^{2m+2}}{(m+1)}=K, \tag{23}$$

where K is an integration constant. The stationary integral is next defined as:

$$J=\int_{-\infty}^{\infty}\left[6P_1g^2-6P_2\left(g'\right)^2-18P_3\left(g''\right)^2+3P_4g^4+2P_5g^6+\frac{6P_6g^{2m+2}}{m+1}\right]dx. \tag{24}$$

SVP states that the solution of the perturbed concatenation model given by (1) will be the same as that of its unperturbed version, namely with $\lambda=\theta_j=0$, as given by (2). However, the amplitude (A) and the inverse width (B) of the perturbed soliton will change, and their variations can be recovered from the solution of the coupled system [6, 7]:

$$\frac{\partial J}{\partial A}=0, \tag{25}$$

and

$$\frac{\partial J}{\partial B}=0. \tag{26}$$

Now, the solution of the unperturbed concatenation model is given by (2). Performing the integration in (24) leads to the stationary integral being evaluated as:

$$
\begin{aligned}
J=&\frac{12P_1A^2}{B}+\frac{4P_4A^4}{B}+\frac{32P_5A^6}{15B}\\
&+\frac{12mP_6A^{2m+2}}{(2m+1)(m+1)B}\frac{\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{\Gamma\left(m+\frac{1}{2}\right)}\\
&-4P_2A^2B-\frac{148P_3A^2B^3}{5}.
\end{aligned}
\tag{27}
$$

Given the stationary integral by (27), the relations (25) and (26) produce:

$$
\begin{aligned}
&6P_1+4A^2P_3+\frac{16A^4P_5}{5}+\frac{3mA^{2m}P_6}{(2m+1)}\frac{\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{\Gamma\left(m+\frac{1}{2}\right)}\\
&-2B^2P_2-\frac{74B^4P_3}{5}=0,
\end{aligned}
\tag{28}
$$

and

$$
\begin{aligned}
&-3P_1-A^2P_4-\frac{8A^4P_5}{15}-\frac{3mA^{2m}P_6}{(2m+1)(m+1)}\frac{\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{\Gamma\left(m+\frac{1}{2}\right)}\\
&-B^2P_2-\frac{111B^4P_3}{5}=0,
\end{aligned}
\tag{29}
$$

respectively. Upon uncoupling (28) and (29), one recovers the amplitude–width relation of the perturbed bright 1–soliton as:

$$
B=\left[\frac{-4P_2+\sqrt{25(P_2)^2-148P_3\left\{\begin{aligned}&45P_1+15A^2P_4+8A^4P_5\\&+\frac{45mA^{2m}\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{(m+1)(2m+1)\Gamma\left(m+\frac{1}{2}\right)}\end{aligned}\right\}}}{222P_3}\right]^{\frac{1}{2}},
\tag{30}
$$

and are subject to the several parameter constraints listed throughout. Additionally, the amplitude–width relation (30) prompts two constraints that are given by:

$$
P_3\left[4P_2-\sqrt{25(P_2)^2-148P_3\left\{\begin{aligned}&45P_1+15A^2P_4+8A^4P_5\\&+\frac{45mA^{2m}\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{(m+1)(2m+1)\Gamma\left(m+\frac{1}{2}\right)}\end{aligned}\right\}}\right]<0,
\tag{31}
$$

together with

$$
25(P_2)^2-148P_3\left\{\begin{aligned}&45P_1+15A^2P_4+8A^4P_5\\&+\frac{45mA^{2m}\Gamma(m)\Gamma\left(\frac{1}{2}\right)}{(m+1)(2m+1)\Gamma\left(m+\frac{1}{2}\right)}\end{aligned}\right\}>0.
\tag{32}
$$

Finally, the perturbed bright 1-soliton solution is given by (2), where the relation between the amplitude A and its inverse width B is in (30) with the parameter constraints that are exhibited throughout.

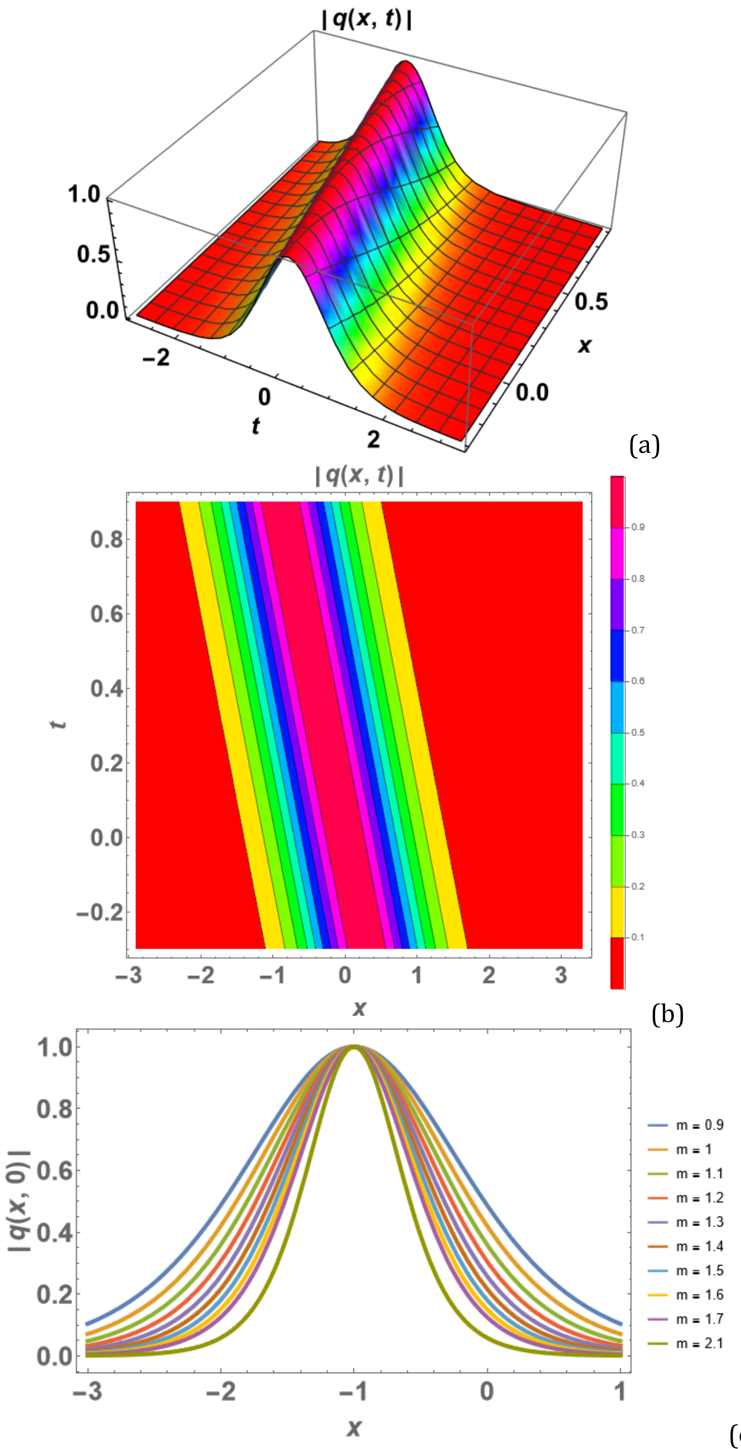

Fig. 1. Profile of a bright soliton solution. We explore and analyze the evolution of the bright soliton solution for the complex-valued solution described by Eq. (2). Our discussion is supported by surface plot (a), contour plot (b), and 2D plot (c) shown in Fig. 1, with the arbitrary intensity factor m. The parameters used for these simulations are as follows: $A=1$, $m=1$, $\kappa=1$, $\omega=1$, $\alpha=-6.1$, $b=1$, $\delta_1=1$, $\delta_2=1$, $\delta_3=1$, $\sigma_1=4$, $\sigma_2=5$, $\sigma_3=-1$, $\sigma_4=1$, $\sigma_5=1$, $\sigma_6=6$, $\sigma_7=1$, $\sigma_8=1$, $\sigma_{12}=-2.5$ and $\sigma_{14}=1$.

4. Conclusions

The paper recovered the bright 1-optical soliton solution to the perturbed dispersive concatenation model addressed with the Kerr law of SPM, while the Hamiltonian perturbation terms are with arbitrary intensity. The perturbation terms, even though of Hamiltonian type, cannot render the model integrable simply because of arbitrary intensity. Thus, SVP has rescued from this hurdle. The 1-soliton solution thus recovered is not exact, although it is an analytical. This salvages when an analytical solution is necessary, such as in the telecommunications industry, where such mathematical models are visible and studied. The results that are recovered in the paper are extendable for further analytical studies in the future.

It must be noted that SVP fails to recover dark and singular 1-soliton solution to the model. The stationary integral in those cases is rendered to be divergent. Later, the dispersive concatenation model will be generalized to power–law of SPM and the same principle will be implemented to derive the bright 1–soliton solutions to its perturbed version when the Hamiltonian perturbation terms carry a different parameter than the homogeneous model. Such studies are underway, and the results will be disseminated after relating them to the pre-existing ones [8, 9].

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***Анотація**. У поточній статті отримане яскраве 1-солітонне рішення в моделі збуреної дисперсійної конкатенації із законом Керра самофазової модуляції за допомогою напівінверсного варіаційного принципу. Члени збурення мають гамільтонівський тип і з'являються з довільною інтенсивністю. Представлено обмеження параметрів, які природно випливають з аналізу.*

***Ключові слова**: солітони, дисперсійна конкатенація, стаціонарний інтеграл*