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DERIVATION AND SOLITON DYNAMICS OF A NEW NON-ISOSPECTRAL AND VARIABLE-COEFFICIENT SYSTEM

by

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> Original scientific paper https://doi.org/10.2298/TSCI180510076X

Under investigation in this paper is a new and more general non-isospectral and variable-coefficient non-linear integrodifferential system. Such a system is Lax integrable because of its derivation from the compatibility condition of a generalized linear non-isospectral problem and its accompanied time evolution equation which is generalized in this paper by embedding four arbitrary smooth enough functions. Soliton solutions of the derived system are obtained in the framework of the inverse scattering transform method with a time-varying spectral parameter. It is graphically shown the dynamical evolutions of the obtained soliton solutions possess time-varying amplitudes and that the inelastic collisions can happen between two-soliton solutions.

Key words: non-isospectral and variable-coefficient integrodifferenail system, soliton solution, inverse scattering transform method, dynamical evolution

Introduction

Non-linear PDE are often related to some non-linear natural phenomena, for example the celebrated Korteweg-de Vries (KdV) shallow-water wave equation which is used to describe the soliton phenomena is first observed by Russell [1]. In soliton theory, the non-isospectral PDE are a kind of non-linear equations describing the solitary waves in a certain type of non-uniform media, while the isospectral PDE often describe solitary waves in lossless and uniform media. Recently, the investigation on derivations and solutions of non-isospectral PDE has attached much attentions [2-15]. In 2017, by introducing a new spectral parameter $ik_t = 0.5$ + $ik - 2k^2$, Zhang and Hong [11] generalized the linear isospectral problem [3]:

$$\phi_x = M\phi, \quad M = \begin{pmatrix} -ik & q \\ r & ik \end{pmatrix}, \quad \phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$
(1)

and its time evolution equation:

$$\phi_t = N\phi, \quad N = \begin{pmatrix} A & B \\ C & -A \end{pmatrix}$$
(2)

where *i* is the imaginary unit, k – the spectral parameter independent of x, q = q(x, t), r = r(x, t) and their derivatives of any order with respect to x and t are smooth functions which vanish as x tends to infinity, and A, B, C are undetermined functions of x, t, q, r, and k.

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Starting from eqs. (1) and (2) equipped with the parameter $ik_t = 0.5 + ik - 2k^2$, Zhang and Hong [11] derived a non-isospectral integrodifferential system:

$$\binom{q}{r}_{t} = \binom{-2q_{x} - xq_{xx} + 2q\partial^{-1}qr + 2xq^{2}r + q + xq_{x} - xq - tq}{2r_{x} + xr_{xx} - 2r\partial^{-1}qr - 2xqr^{2} + r + xr_{x} + xr + tr}$$
(3)

In the present paper, we would like to consider a new and more general non-isospectral and variable-coefficient integrodifferential system:

$$\binom{q}{r}_{l} = \binom{\alpha q_{x} + \beta_{2}(-2q_{x} - xq_{xx} + 2q\partial^{-1}qr + 2xq^{2}r) + \beta_{1}(q + xq_{x}) - \beta_{0}xq}{\alpha r_{x} + \beta_{2}(2r_{x} + xr_{xx} - 2r\partial^{-1}qr - 2xqr^{2}) + \beta_{1}(r + xr_{x}) + \beta_{0}xr}$$
(4)

where $\alpha = \alpha(t)$, $\beta_0 = \beta_0(t)$, $\beta_1 = \beta_1(t)$ and $\beta_2 = \beta_2(t)$ are arbitrary smooth enough functions of *t*. There are maily three starting points of this paper: the first one is to derive system (4) by equipping eqs. (1) and (2) with the generalized spectral parameter, *k* [12]:

$$ik_{t} = \frac{1}{2} \sum_{s=0}^{2} \beta_{s} (2ik)^{s}$$
(5)

and the new generalized function, A:

$$A = \partial^{-1}(r,q) \binom{-B}{C} - \frac{1}{2} \alpha(2ik) - \frac{1}{2} \left[\sum_{s=0}^{2} \beta_s (2ik)^s \right] x \tag{6}$$

the second one is to extend the inverse scattering transform (IST) with the time-varying spectral parameter (5) for constructing soliton solutions of system (4). The last one is to gain some insights into the dynamical evolutions of the obtained soliton solutions. To the best of our knowledge, such a system (4) is new and the IST has not been extended to system (4).

Derivation

Firstly, from the compatibility condition of eqs. (1) and (2) we have:

$$A_{x} = qC - rB - ik_{t}, \ q_{t} = B_{x} + 2ikB + 2qA, \ r_{t} = C_{x} - 2ikC - 2rA$$
(7)

which can be simplified:

$$\begin{pmatrix} q \\ r \end{pmatrix}_{t} = L \begin{pmatrix} -B \\ C \end{pmatrix} - 2ik \begin{pmatrix} -B \\ C \end{pmatrix} + \alpha(2ik) \begin{pmatrix} -q \\ r \end{pmatrix} + \left[\sum_{s=0}^{2} \beta_{s}(2ik)^{s} \right] \begin{pmatrix} -xq \\ xr \end{pmatrix}$$
(8)

by using eqs. (5) and (6).

Secondly, we suppose that:

$$\begin{pmatrix} -B\\ C \end{pmatrix} = \sum_{s=1}^{2} \begin{pmatrix} -b_s\\ c_s \end{pmatrix} (2ik)^{2-s}$$
(9)

and substitute eq. (9) into eq. (8) and then have:

$$(2ik)^{0} : \begin{pmatrix} q \\ r \end{pmatrix}_{t} = L \begin{pmatrix} -b_{2} \\ c_{2} \end{pmatrix} + \beta_{0} \begin{pmatrix} -xq \\ xr \end{pmatrix}$$
(10)

$$(2ik)^{1} : \begin{pmatrix} -b_{2} \\ c_{2} \end{pmatrix} = L \begin{pmatrix} -b_{1} \\ c_{1} \end{pmatrix} + \beta_{1} \begin{pmatrix} -xq \\ xr \end{pmatrix} + \alpha \begin{pmatrix} -q \\ r \end{pmatrix}$$
(11)

$$(2ik)^{2}: \begin{pmatrix} -b_{1} \\ c_{1} \end{pmatrix} = \beta_{2} \begin{pmatrix} -xq \\ xr \end{pmatrix}$$
(12)

by comparing the coefficients of 2ik in eq. (8). Here the operator L is defined by:

$$L = \sigma \partial + 2 \begin{pmatrix} q \\ -r \end{pmatrix} \partial^{-1}(r,q), \quad \partial^{-1} = \frac{1}{2} \begin{pmatrix} x \\ \int_{-\infty}^{x} dx - \int_{x}^{+\infty} dx \end{pmatrix}, \quad \sigma = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$
(13)

Finally, from eqs. (10)-(12) we obtain system (4), which is Lax integrable.

Soliton solutions

Based on eqs. (1), (2), and (5) and the results in [2, 8-13], we have exact solutions:

$$q(x,t) = -2K_1(x,x,t), \quad r(x,t) = \frac{K_{2x}(x,x,t)}{K_1(x,x,t)}$$
(14)

where $K(x, y, t) = [K_1(x, y, t), K_2(x, y, t)]^T$ satisfies Gel'fand-Levitan-Marchenko integral equation:

$$K(x, y, t) - \begin{pmatrix} 0\\1 \end{pmatrix} \overline{F}(x+y, t) + \begin{pmatrix} 0\\1 \end{pmatrix} \int_{x}^{\infty} F(z+x, t) \overline{F}(z+y, t) dz + \\ + \int_{x}^{\infty} K(x, s, t) \int_{x}^{\infty} F(z+s, t) \overline{F}(z+y, t) dz ds = 0$$
(15)

and

$$F(x,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R(k,t) e^{ikx} dk + \sum_{j=1}^{n} c_j^2 e^{i\kappa_j x}, \quad \overline{F}(x,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \overline{R}(k,t) e^{-ikx} dk - \sum_{j=1}^{n} \overline{c}_j^2 e^{-i\overline{\kappa}_j x}$$
(16)

are determined by the scattering data:

$$\left\{\kappa_{j}(t),c_{j}(t),R(k,t)=\frac{a(k,t)}{b(k,t)}, j=1,2,...,n\right\}, \left\{\overline{\kappa}_{m}(t),\overline{c}_{m}(t),\overline{R}(k,t)=\frac{\overline{a}(k,t)}{\overline{b}(k,t)}, m=1,2,...,\overline{n}\right\}$$
(17)

which possess the following time-dependence:

$$\kappa_{jt}(t) = -\frac{i}{2} \sum_{s=0}^{2} \beta_s [2i\kappa_j(t)]^s, \quad i\overline{\kappa}_{mt}(t) = -\frac{i}{2} \sum_{s=0}^{2} \beta_s [2i\overline{\kappa}_m(t)]^s$$
(18)

$$c_{j}^{2}(t) = c_{j}^{2}(0)e^{\int_{0}^{t} \left\{\beta_{i}(w) + 2i\kappa_{j}(w)[\alpha(w) + 2\beta_{2}(w)]\right\}dw}, \quad \overline{c}_{m}^{2}(t) = \overline{c}_{m}^{2}(0)e^{\int_{0}^{t} \left\{\beta_{i}(w) + 2i\overline{\kappa}_{j}(w)[\alpha(w) + 2\beta_{2}(w)]\right\}dw}$$
(19)

$$a(k,t) = a(k,0), \text{ and when } b(k,t) = b(k,0)e^{2i\int_0^t [\alpha(w)k(w)]dw}$$

$$\overline{a}(k,t) = \overline{a}(k,0), \ \overline{b}(k,t) = \overline{b}(k,0)e^{-2i\int_0^t [\alpha(w)k(w)]dw}$$
(20)

where $\kappa_j^2(0)$, $\bar{\kappa}_m^2(0)$, $c_j^2(0)$, $\bar{c}_m^2(0)$, R(k, 0) = b(k, 0)/a(k, 0) and $\bar{R}(k, 0) = \bar{b}(k, 0)/\bar{a}(k, 0)$ are the scattering data of the generalized spectral problem (1) in the case of $[q(x, 0), r(x, 0)]^T$

To construct soliton solutions, as did in [2] we set $R(k, t) = \overline{R}(k, t) = 0$ and have:

$$K_{1}(x, y, t) = -\operatorname{tr}[W^{-1}(x, t)\overline{\Lambda}(x, t)\overline{\Lambda}^{T}(y, t)]$$

$$K_{2}(x, y, t) = i\operatorname{tr}[W^{-1}(x, t)E(x, t)\Lambda(x, t)\overline{\Lambda}^{T}(y, t)]$$
(21)

Then we obtain the following n-soliton solutions of system (5):

$$q(x,t) = 2\operatorname{tr}[W^{-1}(x,t)\overline{\Lambda}(x,t)\overline{\Lambda}^{T}(x,t)]$$
(22)

$$r(x,t) = -\frac{\frac{\mathrm{d}}{\mathrm{d}x} \operatorname{tr}\left[W^{-1}(x,t)P(x,t)\frac{\mathrm{d}}{\mathrm{d}x}P^{T}(x,t)\right]}{\operatorname{tr}\left[W^{-1}(x,t)\overline{\Lambda}(x,t)\overline{\Lambda}^{T}(x,t)\right]}$$
(23)

where tr(·) denotes the trace of a given matrix, E is a $\bar{n} \times \bar{n}$ unit matrix and

$$\Lambda = [c_1(t)e^{i\kappa_1 x}, c_2(t)e^{i\kappa_2 x}, \cdots, c_n(t)e^{i\kappa_n x}]^T, \quad \overline{\Lambda} = [\overline{c_1}(t)e^{-i\overline{\kappa_1} x}, \overline{c_2}(t)e^{-i\overline{\kappa_2} x}, \cdots, \overline{c_n}(t)e^{-i\overline{\kappa_n} x}]^T$$
(24)

$$W(x,t) = E + P(x,t)P^{T}(x,t), \ P(x,t) = \left[\frac{c_{j}(t)\overline{c}_{m}(t)}{\kappa_{j} - \overline{\kappa}_{m}}e^{i(\kappa_{j} - \overline{\kappa}_{m})x}\right]_{\overline{n} \times n}$$
(25)

Particularly, when $n = \bar{n} = 1$ eqs. (22) and (23) give the one-soliton solutions:

$$q = \frac{2\overline{c_{1}^{2}(0)e^{-2i\overline{\kappa_{1}}(t)x-\int_{0}^{t} \{\beta_{1}(w)+2i\overline{\kappa_{j}}(w)[\alpha(w)+2\beta_{2}(w)]\}dw}}{1+\frac{c_{1}^{2}(0)\overline{c_{1}^{2}(0)}}{[\kappa_{1}(t)-\overline{\kappa_{1}}(t)]^{2}}e^{2i[\kappa_{1}(t)-\overline{\kappa_{1}}(t)]x+\int_{0}^{t} \{2i[\kappa_{1}(w)-\overline{\kappa_{j}}(w)][\alpha(w)+2\beta_{2}(w)]\}dw}}$$

$$r = \frac{2c_{1}^{2}(0)e^{2i\kappa_{1}x+\int_{0}^{t} \{\beta_{1}(w)+2i\kappa_{j}(w)[\alpha(w)+2\beta_{2}(w)]\}dw}}{[\kappa_{1}(t)-\overline{\kappa_{1}}(t)]^{2}}e^{2i\kappa_{1}x+\int_{0}^{t} \{\beta_{1}(w)+2i\kappa_{j}(w)[\alpha(w)+2\beta_{2}(w)]\}dw}}$$
(26)

$$r = \frac{c_1^2(0)\overline{c_1}^2(0)}{1 + \frac{c_1^2(0)\overline{c_1}^2(0)}{[\kappa_1(t) - \overline{\kappa_1}(t)]^2}} e^{2i[\kappa_1(t) - \overline{\kappa_1}(t)]x + \int_0^t [2i[\kappa_j(w) - \overline{\kappa_1}(w)][\alpha(w) + 2\beta_2(w)]]dw}$$
(27)

where $\kappa_1(t)$ and $\bar{\kappa}_1(t)$ are , respectively, determined in eq. (18).

In figs. 1-5, the spatial structures and dynmical evolutions of the one-soliton solutions (26) and (27) are shown by selecting $\kappa_1(0) = 1$, $\bar{\kappa}_1(0) = 0.5$, $c_1(0) = -0.1$, $\bar{c}_1(0) = 0.2$, $\alpha = t^2$, $\beta_0 = 1$, $\beta_1 = 1$, and $\beta_2 = 1$.

The spatial structures and dynmical evolutions of the two-soliton solutions determined by eqs. (22) and (23) are shown in figs. 6-10, where $\kappa_1(0) = 1$, $\bar{\kappa}_1(0) = 0.2$, $\kappa_2(0) = -1.2$, $\bar{\kappa}_2(0) = -0.5$, $c_1(0) = -0.3$, $\bar{c}_1(0) = -0.5$, $c_2(0) = 1$, $\bar{c}_2(0) = 2$ and the others are same as figs. 1-5. It is easy to see from figs. 1-10 that the one-soliton solutions and the two-soliton solutions possess time-varying amplitudes. Besides, the inelastic collisions happen between two-soliton solutions.



Figure 1. Spatial structures of one-soliton solutions (26) and (27)

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Figure 4. Dynamical evolutions of one-soliton solution (27) at times; (a) t = -1, (b) t = -0.2

Conclusion

In summary, we have derived and solved the non-isospectral and variable-coefficient integrodifferential system (4). The arbitraryness of the smooth functions $\alpha = \alpha(t)$, $\beta_0 = \beta_0(t)$, $\beta_1 = \beta_1(t)$, and $\beta_2 = \beta_2(t)$ in the obtained *n*-soliton solutions provides with freedom to disscuss the dynamical evolutions of solutions. It is shown when n = 1 and n = 2 the one-soliton solutions and the two-soliton solutions possess time-varying amplitudes and that the inelastic

collisions can happen between two-soliton solutions. To the best of our knowledge, system (4) and solutions (14), (22), and (23) have not been reported in literatures. How to extend the IST method to the non-linear PDE with non-integer derivatives [16-18] is worthy of study.



Figure 5. Dynamical evolutions of one-soliton solution (27) at times; (a) t = 0.5, (b) t = 1.5



Figure 6. Spatial structures of two-soliton solutions determined by (22) and (23)



Figure 7. Dynamical evolutions of two-soliton solution determined by (22) at times; (a) t = -0.1, (b) t = 0.1



Figure 8. Dynamical evolutions of two-soliton solution determined by (22) at times; (a) t = 0.3, (b) t = 0.4







Figure 10. Dynamical evolutions of two-soliton solution determined by (23) at times; (a) t = -0.1, (b) t = 0.5

Acknowledgment

This work was supported by the Natural Science Foundation of China (11547005), the Natural Science Foundation of Liaoning Province of China (20170540007), the Natural Science Foundation of Education Department of Liaoning Province of China (LZ2017002) and Innovative Talents Support Program in Colleges and Universities of Liaoning Province (LR2016021).

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Nomenclature

d/dt	– the first c	lerivativ	e,	[-]	

- $E \bar{n} \times \bar{n}$ unit matrix, [-]
- e the base of natural logarithms, [–]
- *i* imaginary unit, [–]
- *j* natural number, [–]
- *k* spectral parameter, [–]

M, N – matrices, [–] n, \bar{n} – positive integers, [–]

n, n – positive integers, [–]

s - ositive integer, [-] T - transposition, [-] t - time, [s] x, y, z - displacements, [m] *Greek symbol*

 π – circumference ratio, [–]

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