

A Note on solutions of the Korteweg – de Vries hierarchy

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Abstract

Solutions of the Korteweg – de Vries hierarchy are discussed. It is shown that results by Wazwaz [Wazwaz A.M. Multiple – soliton solutions of the perturbed KdV equation, Commun Nonlinear Sci Numer Simulat, 2010; 15(9): 3270 – 3273] are the well – known consequences of the full integrability for the Korteweg – de Vries hierarchy.

The Korteweg – de Vries hierarchy can be written as [1, 2]

$$u_t + \frac{\partial}{\partial x} \sum_{n=0}^N t_n L_{n+1}[u] = 0, \quad (1)$$

where t_n , ($n = 0, \dots, N$) are real parameters of equation and the Lenard operator $L_{n+1}[u]$ is determined by the following recursion formula [3, 4]

$$\frac{\partial L_{n+1}[u]}{\partial x} = \left(\frac{\partial^3}{\partial^3 x} + 4u \frac{\partial}{\partial x} + 2 \frac{\partial u}{\partial x} \right) L_n[u], \quad L_0[u] = \frac{1}{2}. \quad (2)$$

Assuming $n = 0$, $n = 1$ and $n = 2$ in Eq. (2) we have the following formulae

$$L_1[u] = u, \quad L_2[u] = u_{xx} + 3u^2, \quad (3)$$

$$L_3[u] = u_{xxxx} + 10uu_{xx} + 5u_x^2 + 10u^3 \quad (4)$$

and so on.

There is the Lax pair for Eq.(1) in the form

$$\psi_{xx} + (\lambda + u)\psi = 0, \quad (5)$$

$$\psi_t = \left(C + \sum_{n=0}^N t_n \sum_{j=0}^n (-4\lambda)^{n-j} L_{j,x}[u] \right) \psi - 2 \left(\sum_{n=0}^N t_n \sum_{j=0}^n (-4\lambda)^{n-j} L_j[u] \right) \psi_x, \quad (6)$$

where we denote

$$L_{j,x}[u] = \frac{\partial}{\partial x} L_j[u].$$

In the case $N = 2$ the system equation (5) – (6) takes the form

$$\psi_{xx} + (\lambda + u)\psi = 0, \quad (7)$$

$$\begin{aligned} \psi_t = & [C + (t_1 - 4\lambda t_2) u_x + t_2 (u_{xxx} + 6u u_x)] \psi - \\ & - 2 [0.5 t_0 - 2\lambda (t_1 - 4\lambda t_2) + (t_1 - 4\lambda t_2) u + t_2 (u_{xx} + 3u^2)] \psi_x. \end{aligned} \quad (8)$$

Using the compatibility condition

$$(\psi_{xx})_t = (\psi_t)_{xx}$$

for the system of equation (5)–(6) we obtain the Korteweg–de Vries hierarchy (1). In the case $N = 2$ we have the fifth order Korteweg – de Vries equation in the form

$$u_t + t_0 u_x + t_1 (u u_x + u_{xxx}) + t_2 (30u^2 u_x + 10u u_{xxx} + 20u_x u_{xx} + u_{xxxxx}) = 0 \quad (9)$$

Assuming $t_0 = 0$, $t_1 = 1$ and $t_2 = \varepsilon$ in Eq.(9) we have the "perturbed KdV equation" by Wazwaz [5]. We can see that that Eq.(9) is the partial case of the Korteweg – de Vries hierarchy (1).

Every member of the Korteweg–de Vries hierarchy (1) (case $t_0=t_1=t_2=\dots=t_{N-1}=0$ and $t_n=1$) and the Lax pair for them was firstly introduced in [3]. The Korteweg–de Vries hierarchy (1) and Lax pair (5) and (6) is trivial generalization of the results by Lax.

It is well known that the Cauchy problem for every member of the Korteweg–de Vries hierarchy can be solved by means of the inverse scattering transform method. It is known that there are rational, special and soliton solutions of these equations [1,2,6–13].

It is clear that the Cauchy problem for the Korteweg – de Vries hierarchy (1) can be solved by means of the inverse scattering transform method as well taking Lax pair (5)–(6) into account.

Assuming $\lambda = -k^2$ and $u = u_x = u_{xx} = \dots = 0$ we have from Eq.(5)

$$\psi(x, k, t) = C_1(k, t) e^{kx} + C_2(k, t) e^{-kx}. \quad (10)$$

Substituting Eq.(10) into Eq.(6) we obtain the system of equations in the form

$$\frac{d \ln C_2}{dt} - C - \sum_{n=1}^N 2^{2n} t_n k^{2n+1} \quad (11)$$

$$\frac{d \ln C_1}{dt} - C + \sum_{n=1}^N 2^{2n} t_n k^{2n+1} \quad (12)$$

From the system of equations (11) and (12) we find the time evolution of the scattering data for solving the Cauchy problem to the Korteweg – de Vries hierarchy

$$\begin{aligned} \kappa_j = & Const, \quad C_j(t) = C_j(0) \exp \left(t \sum_{n=1}^N 2^{2n} t_n \kappa_n^{2n+1} \right), \\ (j = 0, 1, \dots, J), \quad b(k, t) = & b(k, 0) \exp \left(i t \sum_{n=1}^N 2^{2n+1} t_n k^{2n+1} \right), \end{aligned} \quad (13)$$

where $i^2 = -1$, κ_j are values of the discrete spectrum, $C_j(0)$, ($j = 0, 1, \dots, J$) are the normalisation constants determined at $t = 0$ and $b(k, 0)$ is the reflection coefficient.

The Cauchy problem for the Korteweg – de Vries hierarchy (1) can be solved taking into account the scattering data (13) and the well – known inverse scattering transform method for the Korteweg – de Vries equation [4, 8, 14]. Multi – soliton solutions of the Korteweg – de Vries hierarchy (1) can be found using the scattering data for the reflectionless potentials at $b(k, t) = 0$ [4, 8, 14].

Multi – soliton solution of the Korteweg – de Vries hierarchy (1) can also be found using the well – known formula by Hirota

$$u = 2 (\ln F)_{xx}. \quad (14)$$

Assuming $F(x, t)$ in the form [15]

$$F_1 = 1 + C_1 e^{\theta_1}, \quad \theta_1 = k_1 x - \sum_{n=1}^N t_n k_1^{2n+1} t + k_1 x_1^{(0)} \quad (15)$$

where C_1 and $x_1^{(0)}$ are arbitrary constant, we obtain one soliton solution.

Taking into account $F(x, t)$ in the form [15]

$$F_1 = 1 + C_1 e^{\theta_1} + C_2 e^{\theta_2} + C_1 C - 2 e^{\theta_1 + \theta_2 + A_{12}}, \quad e^{A_{12}} = \frac{(k_1 - k_2)^2}{(k_1 + k_2)^2}, \quad (16)$$

where C_1 and C_2 are arbitrary constants and

$$\theta_j = k_j x - \sum_{n=1}^N t_n k_j^{2n+1} t + k_j x_j^{(0)}, \quad (17)$$

we have two soliton solution and so on.

Rational solutions of hierarchy (1) can be found taking the generalized Yablonskii – Vorob'ev polynomials [11, 12]. There are solutions expressed via the higher Painlevé transcendent functions [9, 10].

In discussion author [5] say that "Multiple – soliton solutions and multiple singular soliton solutions were derived. It was formally proved that this equation is completely integrable equation". We agree with author completely but we saw that his results are consequence of the integrability for the Korteweg – de Vries hierarchy (1). In this paper we have pointed out additionally to works [16–20] the danger in finding exact solutions of the well – known equations.

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