Research Article

On the Solutions and Conservation Laws of a Coupled Kadomtsev-Petviashvili Equation

Chaudry Masood Khalique

Department of Mathematical Sciences, International Institute for Symmetry Analysis and Mathematical Modelling, North-West University, Mafikeng Campus, Private Bag X 2046, Mmabatho 2735, South Africa

Correspondence should be addressed to Chaudry Masood Khalique; masood.khalique@nwu.ac.za

Received 6 October 2012; Accepted 2 December 2012

Academic Editor: Asghar Qadir

Copyright © 2013 Chaudry Masood Khalique. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

A coupled Kadomtsev-Petviashvili equation, which arises in various problems in many scientific applications, is studied. Exact solutions are obtained using the simplest equation method. The solutions obtained are travelling wave solutions. In addition, we also derive the conservation laws for the coupled Kadomtsev-Petviashvili equation.

1. Introduction

The well-known Korteweg-de Vries (KdV) equation [1]

\[ u_t + 6uu_x + u_{xxx} = 0 \] (1)

governs the dynamics of solitary waves. Firstly, it was derived to describe shallow water waves of long wavelength and small amplitude. It is a crucial equation in the theory of integrable systems because it has infinite number of conservation laws, gives multiple-soliton solutions, and has many other physical properties. See, for example, [2] and references therein.

An essential extension of the KdV equation is the Kadomtsev-Petviashvili (KP) equation given by [3]

\[ (u_t + 6uu_x + u_{xxx})_x + u_{yy} = 0. \] (2)

This equation models shallow long waves in the x-direction with some mild dispersion in the y-direction. The inverse scattering transform method can be used to prove the complete integrability of this equation. This equation gives multiple-soliton solutions.

Recently, the coupled Korteweg-de Vries equations and the coupled Kadomtsev-Petviashvili equations, because of their applications in many scientific fields, have been the focus of attention for scientists and as a result many studies have been conducted [4–9].

In this paper, we study a new coupled KP equation [10]:

\[ \left( u_t + u_{xxx} - \frac{7}{4} uu_x - vv_x + \frac{5}{4} (uv)_x \right)_x + u_{yy} = 0, \] (3a)

\[ \left( v_t + v_{xxx} - \frac{5}{4} uu_x - \frac{7}{4} vv_x + 2(uv)_x \right)_x + v_{yy} = 0, \] (3b)

and find exact solutions of this equation. The method that is employed to obtain the exact solutions for the coupled Kadomtsev-Petviashvili equation (3a and 3b) is the simplest equation method [11, 12]. Secondly, we derive conservation laws for the system (3a) and (3b) using the multiplier approach [13, 14].

The simplest equation method was introduced by Kudryashov [11] and later modified by Vitanov [12]. The simplest equations that are used in this method are the Bernoulli and Riccati equations. This method provides a very effective and powerful mathematical tool for solving nonlinear equations in mathematical physics.

Conservation laws play a vital role in the solution process of differential equations (DEs). The existence of a large number of conservation laws of a system of partial differential equations (PDEs) is a strong indication of its integrability [15]. A conserved quantity was utilized to find the unknown exponent in the similarity solution which could not have been obtained from the homogeneous boundary conditions [16].
Also recently, conservation laws have been employed to find solutions of the certain PDEs [17–19].

The outline of the paper is as follows. In Section 2, we obtain exact solutions of the coupled KP system ((3a) and (3b)) using the simplest equation method. Conservation laws for ((3a) and (3b)) using the multiplier method are derived in Section 3. Finally, in Section 4 concluding remarks are presented.

2. Exact Solutions of ((3a) and (3b)) Using Simplest Equation Method

We first transform the system of partial differential equations ((3a) and (3b)) into a system of nonlinear ordinary differential equations in order to derive its exact solutions.

The transformation

\[ u = F(z), \quad v = G(z), \quad z = t - \rho x + (\rho - 1) y, \]

where \( \rho \) is a real constant, transforms ((3a) and (3b)) to the following nonlinear coupled ordinary differential equations (ODEs):

\[
\begin{align*}
\rho^4 F^{iv}(z) + \frac{5}{4} \rho^2 G(z) F''(z) \\
- \frac{7}{4} \rho^3 F(z) F''(z) + \rho^3 F'(z) \\
- 3 \rho F''(z) + F''(z) + \frac{5}{2} \rho^2 F'(z) G'(z) &= 0, \\
\rho^4 G^{iv}(z) + 2 \rho^3 G(z) F''(z) \\
- \frac{5}{4} \rho^3 F(z) F''(z) + 4 \rho^3 F'(z) G'(z) \\
- \frac{5}{4} \rho^3 F'(z)^2 + 2 \rho^2 F'(z) G''(z) \\
- \frac{7}{4} \rho^2 G(z) G''(z) + \rho^2 G'(z) &= 0.
\end{align*}
\]

(5a)

We now use the simplest equation method [11, 12] to solve the system ((5a) and (5b)) as a result we will obtain the exact solutions of our coupled KP system ((3a) and (3b)). We use the Bernoulli and Riccati equations as the simplest equations.

We briefly recall the simplest equation method here. Let us consider the solutions of ((5a) and (5b)) in the form

\[
\begin{align*}
F(z) &= \sum_{i=0}^{M} A_i (H(z))^i, \\
G(z) &= \sum_{i=0}^{M} B_i (H(z))^i.
\end{align*}
\]

Here \( H(z) \) satisfies the Bernoulli and Riccati equations, \( M \) is a positive integer that can be determined by balancing procedure, and \( \mathcal{A}_0, \ldots, \mathcal{A}_M, \mathcal{B}_0, \ldots, \mathcal{B}_M \) are constants to be determined. The solutions of the Bernoulli and Riccati equations can be expressed in terms of elementary functions.

We first consider the Bernoulli equation:

\[
H' (z) = aH(z) + bH^2(z),
\]

(7)

where \( a \) and \( b \) are constants. Its solution can be written as

\[
H(z) = a \left\{ \cosh \left[ a(z + C) \right] + \sinh \left[ a(z + C) \right] \right\}. 
\]

(8)

Secondly, for the Riccati equation:

\[
H'(z) = aH^2(z) + bH(z) + c
\]

(9)

\((a, b, \text{ and } c \text{ are constants}), \text{ we shall use the solutions}

\[
H(z) = -\frac{b}{2a} - \frac{\theta}{2a} \tanh \left[ \frac{1}{2} \theta (z + C) \right] + \frac{1}{C} \cosh (\theta z/2) - \frac{2\theta}{C} \sinh (\theta z/2),
\]

(10)

where \( \theta^2 = b^2 - 4ac > 0 \) and \( C \) is a constant of integration.

2.1. Solutions of ((3a) and (3b)) Using the Bernoulli Equation as the Simplest Equation. In this case the balancing procedure yields \( M = 2 \) so the solutions of ((5a) and (5b)) are of the form

\[
\begin{align*}
F(z) &= \mathcal{A}_0 + \mathcal{A}_1 H + \mathcal{A}_2 H^2, \\
G(z) &= \mathcal{B}_0 + \mathcal{B}_1 H + \mathcal{B}_2 H^2.
\end{align*}
\]

(11)

Substituting (11) into ((5a) and (5b)) and making use of the Bernoulli equation (7) and then equating all coefficients of the functions \( H' \) to zero, we obtain an algebraic system of equations in terms of \( \mathcal{A}_0, \mathcal{A}_1, \mathcal{A}_2, \mathcal{B}_0, \mathcal{B}_1, \) and \( \mathcal{B}_2. \)
Solving the system of algebraic equations, with the aid of Mathematica, we obtain

\[ a = 1, \quad b = 3, \]
\[ A_0 = \frac{k \left( \rho^4 + \rho^2 - 3\rho + 1 \right)}{\rho^2}, \]
\[ A_1 = \frac{36 A_0 \rho^4}{\rho^4 + \rho^2 - 3\rho + 1}, \]
\[ B_0 = \frac{1}{21312} \times \left\{ -9248 A_0 \rho^9 - 8208 A_0 \rho^8 \
+ 67392 A_0 \rho^7 - 9896 A_0 \rho^6 \
+ 11232 A_0 \rho^6 + 279072 A_0 \rho^5 \
- 75978 A_0 \rho^5 + 67392 A_0 \rho^5 \
- 98496 A_0 \rho^5 - 12663 A_0 \rho^4 \
- 190944 A_0 \rho^4 + 270864 A_0 \rho^4 \
- 67608 A_0 \rho^4 - 49280 A_0 \rho^3 \
+ 2814 A_0 A_1 \rho^3 - 22536 A_0 \rho^2 \
+ 205200 A_0 \rho^2 + 938 A_0 A_1 \rho^2 \
+ 2814 A_0 A_1 \rho + 34704 A_0 \
- 7504 A_0 A_1 + 41472 \rho^{11} \
+ 6912 \rho^{10} + 124416 \rho^9 \
- 352512 \rho^8 + 186624 \rho^7 \
- 705024 \rho^6 + 1285632 \rho^5 \
- 884736 \rho^4 + 1181952 \rho^3 \
- 1645056 \rho^2 + 933120 \rho - 172800 \right\}, \]
\[ B_1 = \frac{A_1}{1022976} \times \left\{ 9849 A_1^2 \rho^3 - 3245184 A_1 \rho^3 \
- 354564 A_1 A_1 \rho^3 + 90144 A_1 \rho^3 \
+ 3752 A_1^2 \rho^2 - 1081728 A_1 \rho^2 \
- 135072 A_1 A_1 \rho^2 + 30048 A_1 \rho^2 \
+ 11256 A_1 \rho - 50652 A_1 A_1 \rho \
+ 90144 A_1 \rho - 25326 A_1^2 \
- 16884 A_1 A_1 - 240384 A_1 + 1665792 \right\}, \]
\[ B_2 = \frac{A_1}{340992} \times \left\{ 9849 A_1^2 \rho^3 - 3245184 A_1 \rho^3 - 354564 A_1 A_1 \rho^3 + 90144 A_1 \rho^3 \
+ 3752 A_1^2 \rho^2 - 1081728 A_1 \rho^2 - 135072 A_1 A_1 \rho^2 + 30048 A_1 \rho^2 \
+ 11256 A_1 \rho - 50652 A_1 A_1 \rho + 90144 A_1 \rho - 25326 A_1^2 \
- 16884 A_1 A_1 - 240384 A_1 + 1665792 \right\}, \]

where \( k \) is any root of \( 469k^3 - 416k^2 + 304k - 256 = 0 \). Consequently, a solution of ((3a) and (3b)) is given by

\[ u(t, x, y) = A_0 + A_1 a \left\{ \frac{\cosh [a (z + C)] + \sinh [a (z + C)]}{1 - b \cosh [a (z + C)] - b \sinh [a (z + C)]} \right\}, \]
\[ (13a) \]
\[ v(t, x, y) = B_0 + B_1 a \left\{ \frac{\cosh [a (z + C)] + \sinh [a (z + C)]}{1 - b \cosh [a (z + C)] - b \sinh [a (z + C)]} \right\}^2, \]
\[ (13b) \]

where \( z = t - \rho x + (\rho - 1) y \) and \( C \) is a constant of integration.

2.2. Solutions of ((3a) and (3b)) Using Riccati Equation as the Simplest Equation. The balancing procedure gives \( M = 2 \) so the solutions of ((5a) and (5b)) are of the form

\[ F(z) = A_0 + A_1 H + A_2 H^2, \]
\[ G(z) = B_0 + B_1 H + B_2 H^2. \]
\[ (14) \]

Substituting (14) into ((5a) and (5b)) and making use of the Riccati equation (9), we obtain algebraic system of equations in terms of \( A_0, A_1, A_2, B_0, B_1, \) and \( B_2 \) by equating all coefficients of the functions \( H^2 \) to zero.
Solving the algebraic equations one obtains
\[ \rho = -1, \]
\[ A_0 = k(8ac + b^2 + 5), \]
\[ A_1 = \frac{12aA_0b}{8ac + b^2 + 5}, \]
\[ B = \frac{aA_1}{b}. \]

\[ B_0 = 3\left(-2048b^2c - 256ab^3 + 208aA_0b \right. \]
\[ - 1280ab + 15A_0A_1 \times (74A_1)^{-1}, \]
\[ B_1 = \frac{A_1(336ab - 29A_1)}{192ab - 6A_1}, \]
\[ B_2 = \frac{1}{17760000} \times \left\{ -270144a^2A_0A_1bc \right. \]
\[ + 1080576a^2A_0A_1c^2 + 50652aA_0A_1b^3 \]
\[ - 84420aA_0A_1b + 5784000aA_1b \]
\[ - 751200aA_0A_1b - 3552000abB_1 \]
\[ + 1350720aA_0A_1c + 6096000aA_0A_1c^2 \]
\[ + 70350A_0A_1c^2 + 313000A_1^2 \]
\[ - 422100A_0A_1c^2 - 3756000A_0A_1c^2 \]
\[ + 28920000A_1^2 + 422100A_0A_1b^4 \]
\[ - 938A_0A_1b^4 - 14070A_0A_1c^2 \]
\[ + 62600A_1b^2 - 480256A_1c^4 \]
\[ - 4006400A_1^2c^2 - 1800960A_0A_1c^2 \]
\[ + 112560A_1^2c^2 \right\}, \quad (15)\]

where \( k \) is any root of \( 469k^3 - 416k^2 + 304k - 256 \) and hence solutions of ((3a) and (3b)) are

\[ u(t,x,y) = A_0 + A_1 \left\{ -\frac{b}{2a} - \frac{\theta}{2a} \tanh \left[ \frac{1}{2} \theta (z + C) \right] \right\} + \frac{\theta}{2a} \tanh \left[ \frac{1}{2} \theta (z + C) \right]^2, \]

\[ (16a) \]

\[ v(t,x,y) = B_0 + B_1 \left\{ -\frac{b}{2a} - \frac{\theta}{2a} \tanh \left[ \frac{1}{2} \theta (z + C) \right] \right\} + \frac{\theta}{2a} \tanh \left[ \frac{1}{2} \theta (z + C) \right]^2, \]

\[ (16b) \]

where \( z = t - px + (p-1)y \) and \( C \) is a constant of integration.

A profile of the solution ((13a) and (13b)) is given in Figure 1. The flat peaks appearing in the figure are an artifact of Mathematica and they describe the singularities of the solution.

### 3. Conservation Laws of ((3a) and (3b))

In this section we present conservation laws for the coupled KP system ((3a) and (3b)) using the multiplier method [13, 14]. First we present some preliminaries which we will need later in this section.

#### 3.1. Preliminaries

We briefly present the notation and pertinent results which we utilize below. For details the reader is referred to [20].

Consider a \( k \)-th order system of PDEs of \( n \)-independent variables \( x = (x_1, x_2, \ldots, x^n) \) and \( m \)-dependent variables \( u = (u^1, u^2, \ldots, u^m) \):

\[ E_{\alpha}(x,u,u_{(1)},\ldots,u_{(\bar{\alpha})}) = 0, \quad \alpha = 1,\ldots,m, \quad (18) \]

where \( u_{(1)}, u_{(2)}, \ldots, u_{(\bar{\alpha})} \) denote the collections of all first, second, \ldots, \( k \)-th order partial derivatives, that is, \( u_{i}^\alpha = D_i(u^\alpha), u_{ij}^\alpha = D_iD_j(u^\alpha), \ldots \) respectively, with the total derivative operator with respect to \( x^i \) given by

\[ D_i = \frac{\partial}{\partial x^i} + u_{i}^\beta \frac{\partial}{\partial u^\beta} + u_{ij}^\beta \frac{\partial}{\partial u_{ij}^\beta} + \cdots, \quad i = 1, \ldots, n, \quad (19) \]

where the summation convention is used whenever appropriate.
The Euler-Lagrange operator, for each \( \alpha \), is given by
\[
\frac{\delta}{\delta u^\alpha} = \frac{\partial}{\partial u^\alpha} + \sum_{i,j} (-1)^i D_{ij} \frac{\partial}{\partial u^\alpha_{ij}},
\]
(20)
\[\alpha = 1, \ldots, m.\]

The \( n \)-tuple vector \( T = (T^1, T^2, \ldots, T^n) \), \( T^j \in \mathcal{A}, j = 1, \ldots, n \), where \( \mathcal{A} \) is the space of differential functions, is a conserved vector of (18) if \( T^j \) satisfies
\[
D_j T^i \Big|_{(18)} = 0.
\]
(21)
Equation (21) defines a local conservation law of system (18). A multiplier \( \Lambda_\alpha(x, u, u_1, \ldots) \) has the property that
\[
\Lambda_\alpha E_\alpha = D_j T^j
\]
(22)
holds identically. In this paper, we will consider multipliers of the zeroth order, that is, \( \Lambda_\alpha = \Lambda_\alpha(t, x, y, u, v) \). The determining equations for the multiplier \( \Lambda_\alpha \) are
\[
\frac{\delta (\Lambda_\alpha E_\alpha)}{\delta u^\alpha} = 0.
\]
(23)

Once the multipliers are obtained the conserved vectors are calculated via a homotopy formula [13, 14].

3.2. Construction of Conservation Laws for ((3a) and (3b)).
We now construct conservation laws for the coupled KP system ((3a) and (3b)) using the multiplier method. For the coupled KP system ((3a) and (3b)), we obtain the zeroth-order multipliers (with the aid of GeM [21]), \( \Lambda_1(t, x, y, u, v) \), \( \Lambda_2(t, x, y, u, v) \) that are given by
\[
\Lambda_1 = f_3(t) + yf_4(t) - y^2 f_5'(t) + 2xf_7(t) + y^3(-f_6'(t)) + 6xyf_8(t),
\]
\[
\Lambda_2 = -y^2 f_1'(t) + 2xf_1(t) + y^3(-f_2'(t)) + 6xyf_2(t) + f_5(t) + yf_6(t),
\]
(24)
where \( f_i, i = 1, 2, \ldots, 8 \) are arbitrary functions of \( t \).

Corresponding to the above multipliers we have the following eight local conserved vectors of ((3a) and (3b)):
\[
T_1^t = \frac{1}{2} \left\{ \left[ -2f_1(t)v + 2xf_1(t)u_x - y^2 f_1'(t)v_x \right] \right\},
\]
\[
T_1^x = \frac{1}{4} \left\{ -8y^2 f_1'(t)u_x v - 8y^2 f_1'(t)v_x u 
+ 16xf_1(t)u_x v + 16xf_1(t)v_x u 
+ 5y^2 f_1'(t)u_x u - 10xf_1(t)u_x u 
+ 7y^2 f_1'(t)v_x v - 14xf_1(t)v_x v
- 16f_1(t)uv + 5f_1(t)u^2 + 2y^2 f_1''(t)v 
- 4xf_1'(t)v + 7f_1(t)v^2 - 8f_1(t)v_{xx} 
+ 8xf_1(t)v_{xxx} + 4xf_1(t)v_x 
- 2y^2 f_1'(t)v_x - 4y^2 f_1'(t)v_{xxx} \right\},
\]
\[ T_1^\nu = 2yf_1'(t)v + 2xf_1(t)v_y - y^2 f_1'(t)v_y, \]
\[ T_2^\nu = \frac{1}{2} \left\{ -6yf_2'(t)v + 6yxf_2(t)v_x + y^3 \left( -f_1'(t) \right) v_x \right\}, \]
\[ T_2^x = \frac{1}{4} \left\{ -8y^3 f_2'(t)u_x v - 8y^3 f_1'(t)v_x u + 48xyf_2(t)u_x v + 48xyf_2(t)v_x u + 5y^3 f_1'(t)u_x u - 30yxf_2(t)u_x u + 7y^3 f_1'(t)v_x v - 42yxf_2(t)v_x v - 48yf_2(t)uv + 15yf_2(t)u^2 + 2y^3 f_2''(t)v - 12yf_2(t)v - 21yf_2(t)v^2 - 24yf_2(t)v_{xx} + 24yf_2(t)v_{xxx} + 12yf_2(t)v \right\}, \]
\[ T_2^y = 3y^2 f_2'(t)v - 6xf_2(t)v + 6xyf_2(t)v_y - y^3 f_1'(t)v_y, \]
\[ T_3^x = \frac{1}{4} \left\{ 5f_3(t)u_x v + 5f_3(t)v_x u - 7f_3(t)u_x u - 4f_3(t)v_x v - 2f_3'(t)u_x + 4f_3(t)u_{xx} + 2f_3(t)u_t \right\}, \]
\[ T_3^y = f_3(t)u_y, \]
\[ T_4^x = \frac{1}{2} yf_4(t)u_x, \]
\[ T_4^y = \frac{1}{4} \left\{ 5yf_4(t)u_x v + 5yf_4(t)v_x u - 7yf_4(t)u_x u - 4yf_4(t)v_x v - 2yf_4' u + 4yf_4(t)u_{xx} + 2yf_4(t)u_t \right\}, \]
\[ T_4^y = yf_4(t)u_y - f_4(t)u, \]
\[ T_5^x = \frac{1}{2} f_5(t)v_x, \]
\[ T_5^y = f_5(t)v_y, \]
\[ T_6^x = \frac{1}{2} yf_6(t)v_x, \]
\[ T_6^y = \frac{1}{4} \left\{ 8yf_6(t)u_x v + 8yf_6(t)v_x u - 5yf_6(t)u_x u - 7yf_6(t)v_x v - 2f_6'(t)u_x v + 4f_6(t)v_{xx} + 2f_6(t)u_t \right\}, \]
\[ T_7^y = f_7(t)u_y, \]
\[ T_8^x = \frac{1}{2} \left\{ -6yf_8(t)v + 6yf_8(t)v_x - y^3 f_4'(t)u_x \right\}, \]
\[ T_8^y = \frac{1}{4} \left\{ -5y^2 f_8'(t)u_x v - 5y^2 f_4'(t)v_x u + 10xf_7(t)u_x v + 10xf_7(t)v_x u + 7y^2 f_7'(t)u_x u - 14xf_7(t)u_x u + 4y^2 f_7'(t)v_x v - 8xf_7(t)v_x v - 10f_7(t)uv + 2y^3 f_7''(t)u \right\}, \]
\[ T_9^y = 2yf_9(t)u + 2xf_9(t)v_y - y^3 f_9'(t)u_y, \]
\[ T_9^y = \frac{1}{2} \left\{ -6yf_9(t)u + 6yf_9(t)v_x - y^3 f_9'(t)u_x \right\}, \]
\[ T_{10}^y = \frac{1}{4} \left\{ -5y^2 f_9'(t)u_x v - 5y^2 f_9'(t)v_x u + 30yf_8(t)u_x v + 30yf_8(t)v_x u + 7y^3 f_9'(t)u_x u - 42yf_8(t)u_x u + 4y^3 f_9'(t)v_x v - 24yf_8(t)v_x v - 30yf_8(t)uv + 2y^3 f_9'' u + 12yf_9(t)u - 21yf_9(t)u^2 + 12yf_9(t)v^2 - 24yf_9(t)v_{xx} + 24yf_9(t)v_{xxx} + 12yf_9(t)v \right\}, \]
\[ T_{10}^y = 3y^2 f_9'(t)u - 6xf_9(t)u + 6xf_9(t)v_x - y^3 f_9'(t)u_y, \]

(25)
We note that because of the arbitrary functions $f_i, i = 1, 2, \ldots, 8$ in the multipliers, we obtain an infinitely many conservation laws for the coupled KP system ((3a) and (3b)).

4. Concluding Remarks

The coupled Kadomtsev-Petviashvili system ((3a) and (3b)) was studied in this paper. The simplest equation method was used to obtain travelling wave solutions of the coupled KP system ((3a) and (3b)). The simplest equations that were used in the solution process were the Bernoulli and Riccati equations. However, it should be noted that the solutions ((13a) and (13b)), ((16a) and (16b)), and ((17a) and (17b)) obtained by using these simplest equations are not connected to each other. We have checked the correctness of the solutions obtained here by substituting them back into the coupled KP system ((3a) and (3b)). Furthermore, infinitely many conservation laws for the coupled KP system ((3a) and (3b)) were derived by employing the multiplier method. The importance of constructing the conservation laws was discussed in the introduction.

Acknowledgments

C. M. Khalique would like to thank the Organizing Committee of Symmetries, Differential Equations, and Applications: Galois Bicentenary (SDEA2012) Conference for their kind hospitality during the conference.

References

Submit your manuscripts at
http://www.hindawi.com