Research Article

Conditional Lie-Bäcklund Symmetry Reductions and Exact Solutions of a Class of Reaction-Diffusion Equations

Xinyang Wang¹ and Junquan Song²

¹College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
²Department of Applied Mathematics, Zhejiang University of Technology, Hangzhou 310023, China

Correspondence should be addressed to Junquan Song; mathjqsong@163.com

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The method of conditional Lie-Bäcklund symmetry is applied to solve a class of reaction-diffusion equations

\[ u_t + u_{xx} + Q(x)u_x^2 + P(x)u + R(x) = 0, \]

which have wide range of applications in physics, engineering, chemistry, biology, and financial mathematics theory. The resulting equations are either solved exactly or reduced to some finite-dimensional dynamical systems. The exact solutions obtained in concrete examples possess the extended forms of the separation of variables.

1. Introduction

In this paper, we analyze a class of reaction-diffusion equations (RDEs)

\[ u_t + u_{xx} + Q(x)u_x^2 + P(x)u + R(x) = 0, \]

which admit certain conditional Lie-Bäcklund symmetries (CLBSs). Equation (1) can be simplified from the following RDEs:

\[ u_t + F(x)u_{xx} + Q(x)u_x^2 + G(x)u_x + P(x)u + R(x) = 0, \]

which have wide range of applications in physics, engineering, chemistry, biology, and financial mathematics theory [1–5]. Here the coefficient functions depend upon the variable \( x \) which typically represents the value of the underlying asset, such as the price of a stock upon which an option is placed. There exist several special cases of (2), say, the Black-Scholes-Merton equation, the Longstaff equation [6], the Vasicek equation [7], and the Cox-Ingersoll-Ross equation [8], in which \( Q(x) \) is zero. In order to keep the computations as simple as and consistent with this requirement, authors in [4] transform (2) into (1) by using an equivalence point transformation, namely, by means of

\[ u(t, x) = U(t, X) + g(x), \quad X = h(x), \]

with

\[ h'(x)^2 = \frac{1}{F(x)}, \]

\[ g'(x) = \frac{F'(x) - 2G(x)}{4Q(x)}, \]

Equation (2) can be transformed into

\[ U_t + U_{xx} + \frac{Q(x)}{F(x)}U_x^2 + P(x)U + R(x) + g(x)P(x) \]

\[ - \frac{G(x)^2}{4Q(x)} + \frac{F'(x)^2}{16Q(x)}, \]

\[ - \frac{F(x)G'(x)}{2Q(x)} + \frac{F(x)G(x)Q'(x)}{2Q(x)^2}, \]

\[ - \frac{F(x)F'(x)Q'(x)}{4Q(x)^2} + \frac{F(x)F''(x)}{4Q(x)} = 0, \]
where the primes denote differentiation with respect to x. Then, with the inverse transformation $x = h^{-1}(X)$, this equation can be performed as (1) on reversion to lower case variables and redefinition of the coefficient functions as appropriate. When $Q(x) = \text{constant}$ and $P(x) = 0$, (1) becomes

$$u_t + u_{xx} + ku_x^2 + R(x) = 0,$$

(6)

which can simplify the linear form of

$$v_t + v_{xx} + f(x) v_x = 0,$$

(7)

under the transformation $u = \log(\nu)/k + \int f(x)dx/2k + \nu t$ with $4kR(x) = -(2f' + f^2 + 4k\nu)$.

It is known that symmetry reductions and exact solutions play important roles in the study of RDEs. The conditional Lie-Bäcklund symmetry (CLBS) method introduced by Zhdanov [9] and Fokas and Liu [10, 11] firstly has been proved to be very powerful to classify equations or specify the functions appeared in the equations and construct the corresponding group invariant solutions. Furthermore, authors have shown that CLBS is closely related to the invariantsubspaces; namely, exact solutions defined on invariant subspaces for equations or their variant forms can be obtained by using the CLBS method [12–24].

Motivated by the form of (1), we set the following second-order nonlinear CLBSs:

$$\eta = u_{xx} + a_1(x) u_x^2 + a_2(x) u_x + a_3(x) u + a_4(x),$$

(8)

which are very powerful to specify the functions appeared in (1) and construct the corresponding exact solutions. The remainder of this paper is organized as follows. In Section 2, some equations of the form (1) admitting CLBSs generated by (8) are obtained. CLBS reductions and exact solutions of two concrete examples are used to illustrate the results. Section 3 is devoted to conclusions and discussions.

### 2. Equations Admitting CLBSs and Two Examples

To consider further, we need the following proposition derived in [9, 10].

**Proposition 1.** RDEs (1) admit CLBSs (8) if and only if $\eta E = 0$ whenever $u$ satisfies (1) and $\eta = 0$, where the prime denotes the Gateaux derivative, that is, $\eta E = (d/d\epsilon)|_{\epsilon=0}[u + \epsilon E]$ and $E = -u_{xx} - Q(x)u_x^2 - P(x)u - R(x)$. A direct computation from the above proposition yields

$$\eta E = 2a_1^2 (a_1 - Q) u_x^4 + [2a_1^2 (Q - a_1)$$

$$+ 2a_1 (Q' + 2a_1 a_2 - 2Q a_2) ] u_x^2 + [2a_1^2 (Q - a_1)$$

$$+ a_1 (-P - 4Q a_2 + 2a_1^2 + 4a_1 a_4)$$

$$+ a_2 (3Q' - 2Q a_2 - 4a_1') + a_3 (Q - Q'' + Q''') ] u_x^2$$

$$+ 4a_1 a_3 (a_1 - Q) u u_x^2 + (4a_1 a_2 a_3 - 2a_1 P' + 2Q a_2'$$

$$- 4Q a_2 a_3 - 4a_1' a_3 + 4Q' a_3) u u_x + 2a_1^2 - 2P' + a_2''$$

$$- 2a_1 R' + 2Q a_2' - 2a_2 a_2'$$

$$+ 4a_4 \left(-Q a_2 + a_1 a_2 - a_1' + Q'\right) u_x + 2a_1^2 (a_1 - Q)$$

$$\cdot u^2 + (-a_2 P' - 2a_1 a_3 + a_3' - P'' - 4Q a_3 a_4$$

$$+ 4a_4 a_3 a_4) u + a_4 \left(P - 2Q a_4 - 2a_1' + 2a_1 a_4\right) + a_4''$$

$$- a_3 R - a_1 R' - R'' = 0.$$  

(9)

To vanish all the coefficients of (9), we have the following overdetermined system:

$$2a_1^2 (a_1 - Q) = 0,$$

$$2a_1' (Q - 2a_1) + 2a_1 (Q' + 2a_1 a_2 - 2Q a_2) = 0,$$

$$2a_2' (Q - a_1) + a_1 (-P - 4Q a_4 + 2a_1^2 + 4a_1 a_4)$$

$$+ a_2 (3Q' - 2Q a_2 - 4a_1') + a_3 (Q - Q'' + Q''') = 0,$$

$$4a_1 a_3 (a_1 - Q) = 0,$$

$$4a_1 a_2 a_3 - 2a_1 P' + 2Q a_2' - 4Q a_2 a_3 - 4a_1 a_3$$

$$+ 4Q' a_3 = 0,$$

$$2a_1' - 2P' + a_1'' = 2a_1 R' + 2Q a_2' - 2a_1 a_2'$$

$$+ 4a_4 (-Q a_2 + a_1 a_2 - a_1' + Q') = 0,$$

$$2a_1'' (a_1 - Q) = 0,$$

$$- a_2 P' - 2a_1 a_3 + a_3' - P'' - 4Q a_3 a_4 + 4a_1 a_3 a_4 = 0,$$

$$a_4 (P - 2Q a_4 - 2a_1' + 2a_1 a_4) + a_4'' - a_3 R - a_1 R'$$

$$- R'' = 0.$$  

Solving this system, we can obtain the unknown functions in (1) and the corresponding CLBSs (8). From the first and seventh equations of system (10), it is apparent that the solutions can be divided into two cases including $a_1(x) = Q(x)$ and $a_1(x) = a_1(x) = 0, a_1(x) \neq Q(x)$.

**Case 1** ($a_1(x) = Q(x) = 1$). Substituting $a_1(x), Q(x)$ into the third equation of the above system (10), we can obtain $a_2(x) = P(x)$. Furthermore, we can derive $a_2(x) = \mu_1 / P^{1/2}, P(x) \neq 0$, or $P(x) = 0$ from the eighth equation of (10) by substituting all these.

When $P(x) = 0$, we can obtain $R(x) = (1/2)a_2^2 + a_4 - (1/2)a_1^2 + \mu_1$ from the sixth equation of (10). Then substituting $R(x)$ into (10) again, we obtain $a_2 = 0$ or $a_4 = (1/4)a_1^2 + \mu_1$.
However, there are two unknown functions \( P(x) \), \( a_i(x) \) to be determined with only one determining equation, resulting in

\[
\eta = u_{xx} + u_x^2 + ku + ax + \beta,
\]

When \( P(x) \neq 0 \), substituting \( a_i(x) = \mu_i/P^{(i+1)} \) into the sixth equation of system (10), it arrives at \( R(x) = -\mu_i^2/2P - \mu_i P'/4P^{(i+1)} + a_i + \mu_i \).

\[
\begin{align*}
4\mu_i P^{(i)} & - P'' (18\mu_i P^3 + 4\mu_i P^{(i+1)}) \\
& + \mu_i P' (4P^3 - 8\mu_i P + 16\mu_i^2 a_i) + 10\mu_i^2 P^{(i+1)} P^2 \\
& + 15\mu_i P^{(i+1)} - 4\mu_i^2 P^{(i+2)} - 16\mu_i P^3 a_i \\
& = 0.
\end{align*}
\]

However, there are two unknown functions \( P(x) \), \( a_i(x) \) to be determined with only one determining equation, resulting in

\[
\begin{align*}
a_i &= \frac{1}{16P^{(i+1)}} \left[ -8P^3 P^{(i+1)} \mu_i^2 \\
& + (10P^2 P' P^3 + 8P^4) \mu_i + 4P^2 P^{(i+2)} \\
& + 15P^3 P^{(i+1)} - 4P P^{(i+1)} P^2 - 18P' P^{(i+2)} \\
& - \frac{16P^5 \mu_i}{\mu_i^2} \right] dx + \mu_i P, \quad \mu_i \neq 0.
\end{align*}
\]

Noting that when \( \mu_i = 0 \), it leads to \( \eta = u_{xx} + u_x^2 + P(x)u + R(x) = 0 \), which reveals \( u_t = 0 \) and implies that \( u(x, t) \) is independent of \( t \) which we are not interested. Therefore, it is impossible to obtain the general solutions. However we can solve it explicitly for several special cases.

If \( P(x) = k \), we derive \( a_i = (\sqrt{k}/2)(\mu_i - 2u_k k/\mu_i)x + k \mu_i \).

Then let \( \mu_i = s \sqrt{k}, \mu_i = s(a/k - s/2), \mu_i = s/k^2 + \beta/k \); the solution becomes

\[
\begin{align*}
(i) \quad & u_t + u_{xx} + u_x^2 + ku + ax + \beta = 0, \\
& \eta = u_{xx} + u_x^2 + ku + ax + \beta + k/4.
\end{align*}
\]

If \( P(x) = e^{ax} \), then \( a_i = -(2\mu_i/\lambda \mu_i) e^{(3/2)ax} + (1/4) \lambda x + \mu_i e^{ax} - (\mu_i/\lambda) e^{(1/2)ax} + (\mu_i/4) e^{-ax} - \lambda/16. \)

\]

For \( \lambda \neq 0 \), consequently \( \eta = 0 \) can not be easily solved. If \( P(x) = x^\lambda \) \((\lambda \neq 0, \pm 2)\), then \( a_i = (\lambda/4) e^{[(\lambda+1)/2]x} + (\lambda/2) e^{-(1/2)x} + (\mu_i/4) e^{-\lambda x} \)

\]

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\]

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\]

For \( \lambda \neq 0 \), consequently \( \eta = 0 \) can not be easily solved. If \( P(x) = x^\lambda \) \((\lambda \neq 0, \pm 2)\), then \( a_i = (\lambda/4) e^{[(\lambda+1)/2]x} + (\lambda/2) e^{-(1/2)x} + (\mu_i/4) e^{-\lambda x} \)
Case 1 \((a_1(x) = a_2(x) = 0, P(x) = \text{costant}(= k))\). In this case, after a lengthy calculation, we have
\[
2Qa'_2 - Q'' + 3a_2Q' - 2Qa'_2^2 = 0,
-4Qa_2 + 4Q'a_2 + 2Qa'_2 - 2a'_2a_2 + a''_2 = 0,
-2Qa'_2 - R'' + a'_2 + ka_2 - a_2R' - 2a'_2a_4 = 0.
\]
(Special solutions of the above system are given as follows:

(i) \(u_1 + u_{xx} + x^{-2}u'_2 + ku + a + \beta x^2 = 0, \eta = u_{xx} - x^{-1}u_x, \) \( \eta = (t) \) \( \)
(ii) \(u_1 + u_{xx} + x^2u'_2 + 3/4x^4/ln[x] - 1/x^4 ln[x] + 5/4x^4 - \frac{y^2}{4ln^2[x]} + \gamma/x^2 ln^2[x] + a ln^2[x] + \beta = 0, \eta = u_{xx} + \frac{ln^2[x] - 1}{x ln^2[x]}u_x + \frac{2ln^2[x] - ln[x] - 2 + 2\gamma x^2}{2x^2ln^2[x]} \)
(iii) \(u_1 + u_{xx} + x^2u'_2 + (1/16)\lambda(3\lambda + 4)x^{-2-\lambda} + ax^{-1(2\lambda)-1} + \beta = 0, \eta = u_{xx} + \frac{\lambda}{2}u_x + \frac{1}{8}(2\lambda + \lambda^2)x^{2-\lambda}, \lambda \neq 0, \pm 2; \)
(iv) \(u_1 + u_{xx} + x^2u'_2 + ((3)(\lambda - 1)/4)x^{-2-\lambda} + ax^{-2-\lambda} + \beta = 0, \eta = u_{xx} + \frac{\lambda - 1}{x}u_x + (\lambda - 1)x^{-2-\lambda}, \lambda \neq 0, \pm 2; \)
(v) \(u_1 + u_{xx} + u'_2 + ku - (y^2 - 2\gamma)/4x^2 - (1/2)\gamma k x^2 + ax^2 + \beta = 0, \eta = u_{xx} - \frac{1}{x}u_x + \frac{y}{x^2}. \)

Case 2 \((a_1(x) = a_2(x) = 0, P(x) \neq \text{costant})\). By similar calculation, we can obtain \(a_2(x) = -P'/P \) and \(Q(x) = (\mu_1 P + \mu_2)/P^2\); then system (10) is reduced to
\[
2P' (\mu_1 P + \mu_2) a'_4 + 4 (\mu_1 P^2 - \mu_1 PP' - \mu_2 P^2) a_4 + P''P''P' - P''P'P'' - 2P'' = 0,
\]
\[
P''a'_4 - 2 (\mu_1 P + \mu_2) a'_4 + (2P''P' - 2P'P'' + PP') a_4 + P''P'P'' - P''P'P'' = 0.
\]
(30)

We solve out the result with special cases listed in the following:

(i) \(u_1 + u_{xx} + u'_2 + (ax + \beta)u - (1/12)\alpha x^4 + (1/6)\beta a(\beta - 3\gamma)x^3 + (1/2)\gamma (\beta - 2\gamma)x^2 + \theta_1 x + \theta_2 = 0, \eta = u_{xx} + ax + \gamma, \)
(ii) \(u_1 + u_{xx} + u'_2 + ku + (y^2 - 2\gamma)/4x^2 - (1/2)\gamma k x^2 + ax^2 + \beta = 0, \eta = u_{xx} - \frac{1}{x}u_x + \frac{y}{x^2} + \frac{k}{2}x^2; \)
(iii) \(u_1 + u_{xx} + e^{\lambda x}u'_2 + (a + \beta e^{-\lambda x})u + \beta a(\beta + 4\lambda^2) e^{-2\lambda x} - (y^2/\lambda^2 - (\gamma x/\lambda)(a + \beta e^{-\lambda x}) + \theta e^{-\lambda x} + \theta_2 = 0, \eta = u_{xx} + \lambda u_x + \frac{1}{2}\beta e^{-\lambda x} + \gamma, \lambda \neq 0; \)
(iv) \(u_1 + u_{xx} + e^{\lambda x}u'_2 + (a + \beta e^{-1(2\lambda)x})u + (3/2 + (-6y + 2a)/3\lambda^2) e^{-3(2\lambda) x} - (\beta^2/\lambda^2) e^{-2\lambda x} + ((2\alpha y - 4y)/\lambda^2 + 2\gamma) e^{-\lambda x} + \theta e^{-1(2\lambda)x} + \theta_2 = 0, \eta = u_{xx} + \lambda u_x + \beta e^{-(2\lambda)x} + \gamma, \lambda \neq 0; \)
(v) \(u_1 + u_{xx} + sec^2(\lambda x)u'_2 + (a + \beta sin[\lambda x])u + (2y + (\beta^2 + 6y^2 - 3a\gamma)/\lambda^2 sin^2[\lambda x] - (\beta^2/\lambda^2)sin^2[\lambda x] + (3/2 + (3\gamma - a)/\lambda^2) sin^2[\lambda x] + \gamma sin^2[\lambda x] + \theta_1 sin[\lambda x] + \theta_2 = 0, \eta = u_{xx} + \lambda cot[\lambda x] u_x + \beta sin^2(\lambda x) cos[\lambda x] + \gamma sin^2[\lambda x] + \lambda \neq 0; \)
(vi) \(u_1 + u_{xx} + csc^2(\lambda x)u'_2 + (a + \beta cos[\lambda x])u + (2y + (\beta^2 + 6y^2 - 3a\gamma)/\lambda^2 sin^2[\lambda x] - (\beta^2/\lambda^2) sin^2[\lambda x] + (3/2 + (3\gamma - a)/\lambda^2) sin^2[\lambda x] + \theta_1 cos[\lambda x] + \theta_2 = 0, \eta = u_{xx} + \lambda cot[\lambda x] u_x + \beta sin^2(\lambda x) cos[\lambda x] + \gamma sin^2[\lambda x] + \lambda \neq 0; \)

Thus we have obtained 21 classes of equations (11)-(36) with form (1) which admit certain second-order CLBSs. To reduce and solve equations by means of corresponding CLBSs, one solves \(\eta = 0\) to obtain \(u\) as a function of \(x\) with \(x\)-independent integration constants and then substitutes this solution into (1) to determine the time evolution of these constants. Next, we only present two examples to illustrate this approach.

Example 1. Equation
\[
u_t + u_{xx} + x^2u'_x + ku + \frac{3}{4}kx^2 + a = 0
\]
(37)
admits the CLBS
\[
\eta = u_{xx} + x^{-2}u_x + \frac{k}{2}xu_x + \frac{k^2}{16}x^4 + \frac{3}{4}kx^2.
\]
(38)
The corresponding solutions are given by
\[
\begin{align*}
u(x, t) &= -\frac{1}{16}kx^4 + C_1(t) x + C_2^2(t) ln|x - C_1(t)| \\
&+ C_2(t),
\end{align*}
\]
(39)
where $C_1(t)$ and $C_2(t)$ satisfy the finite-dimensional dynamical system
\[ C'_1 = -\frac{k}{2} C_1, \]
\[ C'_2 = -kC_2 + \frac{k}{2} C_1^2 - a. \]

Exact solutions can be obtained as
\[ C_1 = c_1 e^{-(k/2)t}, \]
\[ C_2 = \left(\frac{1}{2} c_1^2 k t - \frac{a}{k} e^{kt} + c_2\right)e^{-kt} \]
with two arbitrary constants $c_1$ and $c_2$.

**Example 2.** Equation
\[ u_t + u_{xx} + x^2 u_x^2 + ku + a + \beta x^2 = 0 \]
admits the CLBS
\[ \eta = u_{xx} - \frac{1}{x} u_x. \]

The corresponding solutions are given by
\[ u(x, t) = C_1(t) + C_2(t) x^2, \]
where $C_1(t)$ and $C_2(t)$ satisfy the system
\[ C'_1 = -kC_1 - 2C_2 - 4C_1^2 - a, \]
\[ C'_2 = -kC_2 - \beta. \]

This dynamical system can be solved and exact solutions are
\[ C_1 = \frac{1}{k^3} \left[ 4c_1^2 k^2 e^{-2kt} + (8c_2 \beta - 2c_2 tk + c_1 k) k^2 e^{-kt} \right. \]
\[ \left. -ak^2 + 2\beta k - 4\beta^2 \right], \]
\[ C_2 = -\frac{\beta}{k} + c_2 e^{-kt} \]
with two arbitrary constants $c_1$ and $c_2$. Here the solutions $u(x, t)$ preserve the forms of the separation of variables $u = \phi_1(t) + \phi_2(t)\psi(x)$, which are associated with the invariant subspace $\mathcal{L}[1, x^2]$ mentioned in [3] and the references therein.

3. Conclusions and Discussions

In this paper, we have discussed RDEs (1) by means of CLBS with characteristic (8). The key for this method is to determine presumably the form of the CLBS. For (1), we found that nonlinear CLBS (8) is very effective, which can yield some interesting symmetry reductions and exact solutions. Two examples are considered to illustrate this method in terms of the compatibility of CLBSs and the governing equations. Generally speaking, the obtained solutions cannot be derived within the framework of Lie’s classical method and nonclassical method.

In addition, it must be pointed out that, for the corresponding equations with certain fractional derivative [25],
\[ \frac{\partial^\alpha}{\partial t^\alpha} u + u_{xx} + Q(x) u_x^2 + P(x) u + R(x) = 0, \]
\[ 0 < \alpha < 1, \]
we can do similar work including CLBS classification, reductions, and exact solutions.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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