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ON THE CLASSIFICATION OF SYMMETRY REDUCTIONS AND INVARIANT SOLUTIONS FOR THE EULER–LAGRANGE–BORN–INFELD EQUATION¹

We study a connection between the structural properties of the low-dimension ($\dim L \leq 3$) nonconjugate subalgebras of the Lie algebra of the generalized Poincaré group $P(1,4)$ and the results of symmetry reductions for the Euler–Lagrange–Born–Infeld equation. We have performed the classification of nonsingular manifolds in the space $M(1,3) \times R(u)$ invariant with respect to three-dimensional nonconjugate subalgebras of the Lie algebra of the group $P(1,4)$. The results are used for the classification of symmetry reductions and invariant solutions of the Euler–Lagrange–Born–Infeld equation.

Keywords: structural properties of Lie algebras, nonsingular manifolds, classification of symmetry reductions, invariant solutions, Poincaré group $P(1,4)$, Euler–Lagrange–Born–Infeld equation.

1. Introduction

The symmetry reduction is one of the most powerful tools for the investigation of PDEs with nontrivial symmetry groups.

In what follows, we focus our attention on applications of the classical Lie method for symmetry reductions and the construction of invariant solutions of PDEs with non-trivial symmetry groups.

In 1895, S. Lie [1] considered solutions invariant with respect to groups admitted by higher-order PDEs.

According to the classical group analysis, the main classification of symmetry reductions and invariant solutions for PDEs with nontrivial symmetry groups should be performed by using ranks of nonconjugate subalgebras of Lie algebras of symmetry groups of the equations under investigations [2, 3] (see also the references therein). In this approach, the invariant solutions of PDEs with nontrivial symmetry groups are nonsingular manifolds, which are invariant with respect to those nonconjugate subalgebras. Therefore, the classification of invariant solutions reduces to the

classification of the corresponding nonsingular manifolds.

However, it turned out that the reduced equations obtained with the help of nonsingular manifolds, which are invariant with respect to nonconjugate subalgebras of the same ranks of the Lie algebras of the symmetry groups of some PDEs, were of different types. Grundland, Harnad, and Winternitz [4] were the first who pointed out and investigated the similar phenomenon. The details on this theme can be found in [5–13] (see also the references therein).

To try to explain some differences in the properties of the reduced equations and invariant solutions, which are obtained by using nonconjugate subalgebras of the same ranks of the Lie algebras of the symmetry groups of the PDEs under consideration, we recently suggested to use the structural properties of those nonconjugate subalgebras. The details on this theme can be found in [10, 12, 13] (see also the references therein).

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At the present time, the relationship between the structural properties of the three-dimensional nonconjugate subalgebras of the Lie algebra of the group $P(1,4)$ and the properties of the reduced equations for the Euler–Lagrange–Born–Infeld equation has been investigated. We obtained the following types of the reduced equations:

- identities;
- linear ordinary differential equations;
- nonlinear ordinary differential equations;
- partial differential equations.

It should be noted that, from the invariants of some nonconjugate subalgebras of the Lie algebra of the group $P(1,4)$, it is impossible to construct the ansätze which reduce the Euler–Lagrange–Born–Infeld equation.

In this paper, we focus our attention on the reduction of the Euler–Lagrange–Born–Infeld equation to identities. More precisely, we only present the results of the symmetry reduction for those types of subalgebras, which provide us reductions to identities.

2. Lie Algebra of the Poincaré Group $P(1,4)$ and Its Nonconjugate Subalgebras

The group $P(1,4)$ is a group of rotations and translations of the five-dimensional Minkowski space $M(1,4)$. It is the smallest group which contains, as subgroups, the extended Galilei group $\tilde{G}(1,3)$ [14] (the symmetry group of classical physics) and the Poincaré group $P(1,3)$ (the symmetry group of relativistic physics).

The Lie algebra of the group $P(1,4)$ is generated by 15 basis elements $M_{\mu\nu} = -M_{\nu\mu}$ ($\mu, \nu = 0, 1, 2, 3, 4$) and P_μ ($\mu = 0, 1, 2, 3, 4$) which satisfy the commutation relations

$$[P_\mu, P_\nu] = 0,$$

$$[M_{\mu\nu}, P_\sigma] = g_{\nu\sigma}P_\mu - g_{\mu\sigma}P_\nu,$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = g_{\mu\sigma}M_{\nu\rho} + g_{\nu\rho}M_{\mu\sigma} - g_{\mu\rho}M_{\nu\sigma} - g_{\nu\sigma}M_{\mu\rho},$$

where $g_{00} = -g_{11} = -g_{22} = -g_{33} = -g_{44} = 1$, $g_{\mu\nu} = 0$, if $\mu \neq \nu$.

Here, we consider the following representation [15] of the Lie algebra of the group $P(1,4)$:

$$P_0 = \frac{\partial}{\partial x_0}, \quad P_1 = -\frac{\partial}{\partial x_1}, \quad P_2 = -\frac{\partial}{\partial x_2}, \quad P_3 = -\frac{\partial}{\partial x_3},$$

$$P_4 = -\frac{\partial}{\partial u}, \quad M_{\mu\nu} = x_\mu P_\nu - x_\nu P_\mu, \quad x_4 \equiv u.$$

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Below, we will use the following basis elements:

$$G = M_{04}, \quad L_1 = M_{23}, \quad L_2 = -M_{13}, \quad L_3 = M_{12},$$

$$P_a = M_{a4} - M_{0a}, \quad C_a = M_{a4} + M_{0a}, \quad X_0 = \frac{1}{2}(P_0 - P_4),$$

$$X_k = P_k, \quad X_4 = \frac{1}{2}(P_0 + P_4), \quad (a, k = 1, 2, 3).$$

The nonconjugate subalgebras of the Lie algebra of the group $P(1,4)$ have been described in works [16–18].

The Lie algebra of the extended Galilei group $\tilde{G}(1,3)$ is generated by the basis elements

$$L_1, L_2, L_3, P_1, P_2, P_3, X_0, X_1, X_2, X_3, X_4.$$

The classification of all nonconjugate subalgebras of the Lie algebra of the group $P(1,4)$ of dimensions ≤ 3 was performed in [19].

3. On the Classification of Symmetry Reductions for the Euler–Lagrange–Born–Infeld Equation

The Born–Infeld equations in the spaces of various dimensions and various types have many applications in the fluid dynamics, theory of continuous medium, general theory of relativity, field theory, theory of minimal surfaces, nonlinear electrodynamics, theory of conservation laws, *etc.* More details on this theme can be found in [20–24] (see also the references therein).

Let us consider the Euler–Lagrange–Born–Infeld equation of the form

$$\square u (1 - u_\nu u^\nu) + u^\mu u^\nu u_{\mu\nu} = 0,$$

where

$$u = u(x), \quad x = (x_0, x_1, x_2, x_3) \in M(1,3),$$

$$u_\mu \equiv \frac{\partial u}{\partial x^\mu}, \quad u_{\mu\nu} \equiv \frac{\partial^2 u}{\partial x^\mu \partial x^\nu}, \quad u^\mu = g^{\mu\nu} u_\nu,$$

and

$$g_{\mu\nu} = (1, -1, -1, -1)\delta_{\mu\nu}, \quad \mu, \nu = 0, 1, 2, 3,$$

\square is the d’Alembert operator.

In 1984, Fushchich and Serov [15] studied the symmetry properties and constructed some classes of exact solutions for the multidimensional nonlinear Euler–Lagrange equation. It follows from [15] that the Lie algebra of the symmetry group of the Euler–Lagrange–Born–Infeld equation contains, as subalgebra, the Lie algebra of the Poincaré group $P(1,4)$. As

we wrote earlier, the results of the classification of all the low-dimensional ($\dim L \leq 3$) nonconjugate subalgebras of the Lie algebra of the group $P(1, 4)$ can be found in [19].

In order to classify symmetry reductions and invariant solutions for the Euler–Lagrange–Born–Infeld equation, we need the classification of nonsingular manifolds in the space $M(1, 3) \times R(u)$ invariant with respect to nonconjugate subalgebras of the Lie algebra of the group $P(1, 4)$.

Till now, we have performed the classification of nonsingular manifolds in the space $M(1, 3) \times R(u)$ invariant with respect to three-dimensional nonconjugate subalgebras of the Lie algebra of the group $P(1, 4)$ and have used the results for the classification of symmetry reductions and invariant solutions for the Euler–Lagrange–Born–Infeld equation. As we wrote above, we will focus our attention on the reduction of the Euler–Lagrange–Born–Infeld equation to identities. Therefore, we only present the results of the symmetry reduction for those types of subalgebras which provide us reductions to identities.

Now, we present some of the results obtained.

3.1. Lie algebras of the type $3A_1$

Taking the invariants of nine subalgebras into account, we constructed the ansätze which reduce the Euler–Lagrange–Born–Infeld equation to identities.

Below, we present some of the results obtained.

- $\langle P_1 - \gamma X_3, \gamma > 0 \rangle \oplus \langle P_2 - X_2 - \delta X_3, \delta \neq 0 \rangle \oplus \langle X_4 \rangle$:

Ansatz

$$x_3(x_0 + u)^2 - (\gamma x_1 + x_2 \delta - x_3)(x_0 + u) - \gamma x_1 = \varphi(\omega),$$

$$\omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_3(x_0 + u)^2 - (\gamma x_1 + x_2 \delta - x_3)(x_0 + u) - \gamma x_1 = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

- $\langle P_1 - \gamma X_3, \gamma > 0 \rangle \oplus \langle P_2 - X_2 \rangle \oplus \langle X_4 \rangle$:

Ansatz

$$x_3(x_0 + u)^2 - (\gamma x_1 - x_3)(x_0 + u) - \gamma x_1 = \varphi(\omega),$$

$$\omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_3(x_0 + u)^2 - (\gamma x_1 - x_3)(x_0 + u) - \gamma x_1 = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

- $\langle P_1 - X_3 \rangle \oplus \langle P_2 \rangle \oplus \langle X_4 \rangle$:

Ansatz

$$x_3 - \frac{x_1}{x_0 + u} = \varphi(\omega), \quad \omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_3 - \frac{x_1}{x_0 + u} = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

As we see in the above-presented cases, ansätze (1)–(3) (nonsingular manifolds invariant with respect to the corresponding subalgebras) are the solutions of the Euler–Lagrange–Born–Infeld equation.

It should be noted that subalgebras (1)–(3) belong to the Lie algebra of the extended Galilei group $\tilde{G}(1, 3) \subset P(1, 4)$.

3.2. Lie algebras of the type $A_{3.1}$

Taking the invariants of ten nonconjugate subalgebras into account, we constructed the ansätze which reduced the the Euler–Lagrange–Born–Infeld equation to identities.

Below, we present some of the results obtained.

- $\langle 4X_4, P_1 - X_2 - \gamma X_3, P_2 + X_1 - \mu X_2 - \delta X_3, \gamma > 0, \delta \neq 0, \mu > 0 \rangle$:

Ansatz

$$x_3(x_0 + u)^2 - (\gamma x_1 + x_2 \delta - \mu x_3)(x_0 + u) + (\delta - \gamma \mu)x_1 - x_2 \gamma + x_3 = \varphi(\omega), \quad \omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_3(x_0 + u)^2 - (\gamma x_1 + x_2 \delta - \mu x_3)(x_0 + u) + (\delta - \gamma \mu)x_1 - x_2 \gamma + x_3 = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

- $\langle 4X_4, P_1 - X_2 - \gamma X_3, P_2 + X_1 - \mu X_2, \gamma > 0, \mu > 0 \rangle$:

Ansatz

$$x_3(x_0 + u)^2 - (\gamma x_1 - \mu x_3)(x_0 + u) - \gamma \mu x_1 - x_2 \gamma +$$

$$+ x_3 = \varphi(\omega), \quad \omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_3(x_0 + u)^2 - (\gamma x_1 - \mu x_3)(x_0 + u) - \gamma \mu x_1 - x_2 \gamma + x_3 = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

3. $\langle 2\mu X_4, P_3 - X_2, X_1 + \mu X_3, \mu > 0 \rangle$:

Ansatz

$$x_2 - \frac{x_3 - \mu x_1}{x_0 + u} = \varphi(\omega), \quad \omega = x_0 + u.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_2 - \frac{x_3 - \mu x_1}{x_0 + u} = \varphi(x_0 + u),$$

where φ is an arbitrary smooth function.

As we see, in the above-presented cases, ansätze (1)–(3) (nonsingular manifolds invariant with respect to the corresponding subalgebras) are the solutions of the Euler–Lagrange–Born–Infeld equation.

It should be noted that subalgebras (1)–(3) belong to the Lie algebra of the extended Galilei group $\tilde{G}(1, 3) \subset P(1, 4)$.

3.3. Lie algebras of the type $A_{3,6}$

Taking the invariants of two nonconjugate subalgebras into account, we constructed ansätze which reduced the Euler–Lagrange–Born–Infeld equation to identities.

Below, we present some of the result obtained.

$$\langle X_1, -X_2, -(L_3 + 2X_4) \rangle:$$

Ansatz

$$x_0 + u = \varphi(\omega), \quad \omega = x_3.$$

A solution of the Euler–Lagrange–Born–Infeld equation has the form

$$x_0 + u = \varphi(x_3),$$

where φ is an arbitrary smooth function.

As we see in the above-presented case, the ansatz (nonsingular manifold, invariant with respect to the corresponding subalgebra) is a solution of the Euler–Lagrange–Born–Infeld equation.

It should be noted that the subalgebra belongs to the Lie algebra of the extended Galilei group $\tilde{G}(1, 3) \subset P(1, 4)$.

4. Conclusions

We have performed the classification of nonsingular manifolds in the space $M(1, 3) \times R(u)$ invariant with respect to three-dimensional nonconjugate subalgebras of the Lie algebra of the group $P(1, 4)$ and have used the results for the classification of symmetry reductions and invariant solutions for the Euler–Lagrange–Born–Infeld equation.

We have focused our attention on the classification of symmetry reductions of the Euler–Lagrange–Born–Infeld equation to identities. More precisely, we have presented only the results of the symmetry reduction for those types of three-dimensional nonconjugate subalgebras of the Lie algebra of the group $P(1, 4)$ which give reductions to identities. It is known [19] that the Lie algebra of the group $P(1, 4)$ contains three-dimensional nonconjugate subalgebras of the following types: $3A_1, A_2 \oplus A_1, A_{3,1}, A_{3,2}, A_{3,3}, A_{3,4}, A_{3,6}, A_{3,7}^a, A_{3,8},$ and $A_{3,9}$.

From the results obtained, it follows that all above-presented symmetry reductions of the Euler–Lagrange–Born–Infeld equation to identities can be obtained using some subalgebras of the following types: $3A_1, A_{3,1}, A_{3,6}$.

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ПРО КЛАСИФІКАЦІЮ СИМЕТРИЙНИХ
РЕДУКЦІЙ ТА ІНВАРІАНТНИХ РОЗВ’ЯЗКІВ
РІВНЯННЯ ОЙЛЕРА–ЛАГРАНЖА–БОРНА–ІНФЕЛЬДА

Резюме

Вивчається зв’язок між структурними властивостями низьковимірних ($\dim L \leq 3$) неспряжених підалгебр алгебри Лі узагальненої групи Пуанкаре $P(1,4)$ і результатами симетрійних редукцій для рівняння Ойлера–Лагранжа–Борна–Інфельда. Проведено класифікацію несингулярних многовидів в просторі $M(1,3) \times R(u)$, інваріантних відносно тривимірних неспряжених підалгебр алгебри Лі групи $P(1,4)$, і отримані результати використано для класифікації симетрійних редукцій та інваріантних розв’язків рівняння Ойлера–Лагранжа–Борна–Інфельда.