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Quasi-Canonical Biholomorphically Projective Mappings of Generalized Riemannian Space in the Eisenhart Sense

Vladislava M. Milenković [1] and Mića S. Stanković [2,*]

[1] Faculty of Technology, University of Niš, Bulevar oslobodjenja 124, 16000 Leskovac, Serbia; vanja.dunja91@gmail.com or vladislava@tf.ni.ac.rs
[2] Faculty of Sciences and Mathematics, University of Niš, Višegradska 33, 18000 Niš, Serbia
* Correspondence: mica.stankovic@pmf.edu.rs

Abstract: In this paper, quasi-canonical biholomorphically projective and equitorsion quasi-canonical biholomorphically projective mappings are defined. Some relations between the corresponding curvature tensors of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ are obtained. At the end, the invariant geometric object of an equitorsion quasi-canonical biholomorphically projective mapping is found.

Keywords: quasi-canonicalbiholomorphically projective mapping; equitorsion quasi-canonical biholomorphically projective mapping; curvature tensor; invariant geometric object

MSC: Primary 53B05; Secondary 53B20; 53C15

1. Introduction and Preliminaries

Differentiable manifolds GR_N with a non-symmetric metric tensor, GA_N with a non-symmetric affine connection and their mappings were, and still are, the subject of interest of many scientists [1–14]. The use of a non-symmetric basic tensor and non-symmetric connection became especially relevant after the appearance of the works of A. Einstein related to creating the unified field theory, where the symmetric part of the basic tensor is related to gravitation, and the antisymmetric one to electromagnetism. We can say that, after A. Einstein [15,16], the main steps were made by L. P. Eisenhart [17,18].

Geometric mappings are interesting, both theoretically and practically. Geodesic and almost geodesic lines play an important role in geometry and physics [1,2,6,19]. The movement of many types of mechanical systems, as well as bodies or particles in gravitational or electromagnetic fields, in continual constant surroundings, is often conducted in paths, which can be looked upon as geodesic lines of Riemannian or affine connected spaces, which are defined by the energetic regime along which the process takes place. So, for example, two Riemannian spaces, which admit reciprocal geodesic mapping, describe processes which are unfolded by an equivalent exterior load and equal orbit, but different energetic regimes. In this case, one of these processes can be modeled by another. During recent years, many papers have been devoted to the theory of holomorphically projective mappings; let us mention J. Mikeš, S.M. Minčić, M.S. Stanković, Lj. S. Velimirović, M. Lj. Zlatanović, etc. [7,12–14,19]. This paper is a natural continuation of the research published in paper [20] in which biholomorphically projective mappings were studied, and they can be observed as a kind of generalization of holomorphically projective mappings.

A generalized Riemannian space GR_N in the sense of Eisenhart's definition [18] is a differentiable N-dimensional manifold, equipped with a non-symmetric metric tensor g_{ij}. The connection coefficients of the space GR_N are the generalized Cristoffel's symbols of the second kind [19]:

$$\Gamma^i_{jk} = g^{\underline{ip}}\Gamma_{p.jk}, \tag{1}$$

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Citation: Milenković, V.M.; Stanković, M.S. Quasi-Canonical Biholomorphically Projective Mappings of Generalized Riemannian Space in the Eisenhart Sense. *Axioms* **2024**, *13*, 528. https://doi.org/10.3390/axioms13080528

Academic Editor: Anna Maria Fino

Received: 27 June 2024
Revised: 30 July 2024
Accepted: 31 July 2024
Published: 3 August 2024

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where $||g^{\underline{ij}}|| = ||g_{\underline{ij}}||^{-1}$, $g_{\underline{ij}} = \frac{1}{2}(g_{ij} + g_{ji})$ and

$$\Gamma_{i.jk} = \frac{1}{2}(g_{ji,k} - g_{jk,i} + g_{ik,j}),$$

where, for example, $g_{ij,k} = \frac{\partial g_{ij}}{\partial x^k}$. We suppose that $\det||g_{ij}|| \neq 0$, $\det||g_{\underline{ij}}|| \neq 0$. In the general case, the connection coefficients are not symmetric, i.e., $\Gamma^i_{jk} \neq \Gamma^i_{kj}$, and they can be represented as the sum of the symmetric and antisymmetric parts

$$\Gamma^i_{jk} = S^i_{jk} + T^i_{jk}, \tag{2}$$

where the symmetric and antisymmetric part of Γ^i_{jk} are given by the formulas

$$\Gamma^i_{\underline{jk}} = \frac{1}{2}(\Gamma^i_{jk} + \Gamma^i_{kj}) = S^i_{jk}, \quad \Gamma^i_{\underset{\vee}{jk}} = \frac{1}{2}(\Gamma^i_{jk} - \Gamma^i_{kj}) = T^i_{jk}. \tag{3}$$

The magnitude T^i_{jk} is the torsion tensor of the space GR_N.

In a generalized Riemannian space, one can define four kinds of covariant derivatives [9]. For example, for a tensor a^i_j in GR_N we have

$$\begin{aligned}
a^i_{j|_1^m} &= a^i_{j,m} + \Gamma^i_{pm}a^p_j - \Gamma^p_{jm}a^i_p,\\
a^i_{j|_2^m} &= a^i_{j,m} + \Gamma^i_{mp}a^p_j - \Gamma^p_{mj}a^i_p,\\
a^i_{j|_3^m} &= a^i_{j,m} + \Gamma^i_{pm}a^p_j - \Gamma^p_{mj}a^i_p,\\
a^i_{j|_4^m} &= a^i_{j,m} + \Gamma^i_{mp}a^p_j - \Gamma^p_{jm}a^i_p,
\end{aligned} \tag{4}$$

where $|_\theta$ $(\theta = 1, 2, 3, 4)$ denotes a covariant derivative of the kind θ and $a^i_{j,m} = \dfrac{\partial a^i_j}{\partial x^m}$.

In the case of the space GR_N, we have twelve curvature tensors, and S. M. Minčić proved that there are five independent ones. In this paper, we will consider the following five independent curvature tensors [9]:

$$\begin{aligned}
R^i_{1jmn} &= \Gamma^i_{jm,n} - \Gamma^i_{jn,m} + \Gamma^p_{jm}\Gamma^i_{pn} - \Gamma^p_{jn}\Gamma^i_{pm},\\
R^i_{2jmn} &= \Gamma^i_{mj,n} - \Gamma^i_{nj,m} + \Gamma^p_{mj}\Gamma^i_{np} - \Gamma^p_{nj}\Gamma^i_{mp},\\
R^i_{3jmn} &= \Gamma^i_{jm,n} - \Gamma^i_{nj,m} + \Gamma^p_{jm}\Gamma^i_{np} - \Gamma^p_{nj}\Gamma^i_{pm} + \Gamma^p_{mn}(\Gamma^i_{pj} - \Gamma^i_{jp}),\\
R^i_{4jmn} &= \Gamma^i_{jm,n} - \Gamma^i_{nj,m} + \Gamma^p_{jm}\Gamma^i_{np} - \Gamma^p_{nj}\Gamma^i_{pm} + \Gamma^p_{nm}(\Gamma^i_{pj} - \Gamma^i_{jp}),\\
R^i_{5jmn} &= \frac{1}{2}(\Gamma^i_{jm,n} + \Gamma^i_{mj,n} - \Gamma^i_{jn,m} - \Gamma^i_{nj,m}\\
&\quad + \Gamma^p_{jm}\Gamma^i_{pn} - \Gamma^p_{jn}\Gamma^i_{mp} + \Gamma^p_{mj}\Gamma^i_{pn} - \Gamma^p_{nj}\Gamma^i_{pm}).
\end{aligned} \tag{5}$$

Let GR_N and $G\overline{R}_N$ be two generalized Riemannian spaces. We will observe these spaces in the common system of coordinates defined by the mapping $f : GR_N \to G\overline{R}_N$. If Γ^h_{ij} and $\overline{\Gamma}^h_{ij}$ are connection coefficients of the spaces GR_N and $G\overline{R}_N$, respectively, then

$$P^h_{ij} = \overline{\Gamma}^h_{ij} - \Gamma^h_{ij} \tag{6}$$

is the deformation tensor of the connection for a mapping f.

The relations between the corresponding curvature tensors of the spaces GR_N and $G\overline{R}_N$ are obtained in [19] as follows:

$$\begin{aligned}
\overline{R}^{i}_{1\,jmn} &= R^{i}_{1\,jmn} + P^{i}_{jm|n\,1} - P^{i}_{jn|m\,1} + P^{p}_{jm}P^{i}_{pn} - P^{p}_{jn}P^{i}_{pm} + 2T^{p}_{mn}P^{i}_{jp},\\
\overline{R}^{i}_{2\,jmn} &= R^{i}_{2\,jmn} + P^{i}_{mj|n\,2} - P^{i}_{nj|m\,2} + P^{p}_{mj}P^{i}_{np} - P^{p}_{nj}P^{i}_{mp} + 2T^{p}_{nm}P^{i}_{pj},\\
\overline{R}^{i}_{3\,jmn} &= R^{i}_{3\,jmn} + P^{i}_{jm|n\,2} - P^{i}_{nj|m\,1} + P^{p}_{jm}P^{i}_{np} - P^{p}_{nj}P^{i}_{pm} + 2P^{p}_{nm}(T^{i}_{pj} + \underset{\vee}{P^{i}_{pj}}),\\
\overline{R}^{i}_{4\,jmn} &= R^{i}_{4\,jmn} + P^{i}_{jm|n\,2} - P^{i}_{nj|m\,1} + P^{p}_{jm}P^{i}_{np} - P^{p}_{nj}P^{i}_{pm} + 2P^{p}_{mn}(T^{i}_{pj} + \underset{\vee}{P^{i}_{pj}}),\\
\overline{R}^{i}_{5\,jmn} &= R^{i}_{5\,jmn} + \frac{1}{2}(P^{i}_{jm|n\,3} - P^{i}_{jn|m\,4} + P^{i}_{mj|n\,4} - P^{i}_{nj|m\,3}\\
&\quad + P^{p}_{jm}P^{i}_{pn} - P^{p}_{jn}P^{i}_{mp} + P^{p}_{mj}P^{i}_{np} - P^{p}_{nj}P^{i}_{pm}),
\end{aligned} \tag{7}$$

where P^{h}_{ij} is a deformation tensor for a mapping f, $\underset{\vee}{P^{h}_{ij}}$ is its antisymmetric part and T^{h}_{ij} is a torsion tensor.

2. Quasi-Canonical Biholomorphically Projective Mappings

In paper [20], we define biholomorphically projective mappings between two generalized Riemannian spaces GR_N and $G\overline{R}_N$ with almost complex structures that are equal in a common system of coordinates defined by the mapping $f : GR_N \to G\overline{R}_N$. We have considered a generalized Riemannian space GR_N with a non-symmetric metric tensor g_{ij} and almost complex structure F^{h}_{i} such that $F^{h}_{i} \neq a\delta^{h}_{i}$, where a is scalar invariant, and we have defined the biholomorphically projective curve of the kind θ $(\theta = 1, 2)$ and the biholomorphically projective mapping of the kind θ $(\theta = 1, 2)$.

Definition 1 ([20]). *In the space GR_N, a curve l given in parametric form*

$$x^{i} = x^{i}(t),\ (i = 1, ..., N),$$

is said to be biholomorphically projective of the kind θ $(\theta = 1, 2)$ if it satisfies the following equation:

$$\lambda^{h}_{\underset{\theta}{|p}}(t)\lambda^{p}(t) = a(t)\lambda^{h}(t) + b(t)F^{h}_{p}\lambda^{p}(t) + c(t)\overset{2}{F}{}^{h}_{p}\lambda^{p}(t),$$

where a, b and c are functions of parameter t, $\lambda^{i} = \dfrac{dx^{i}}{dt}$ and $\overset{2}{F}{}^{h}_{p} = F^{h}_{q}F^{q}_{p}$.

Definition 2 ([20]). *A diffeomorphism $f : GR_N \to G\overline{R}_N$ is a biholomorphically projective mapping of the kind θ $(\theta = 1, 2)$ if biholomorphically projective curves of the kind θ $(\theta = 1, 2)$ of the space GR_N are mapped to the biholomorphically projective curves of the kind θ of the space $G\overline{R}_N$.*

Since it holds [20]

$$\lambda^{h}_{\underset{1}{|p}}\lambda^{p} = \frac{d\lambda^{h}}{dt} + \Gamma^{h}_{pq}\lambda^{p}\lambda^{q} = \lambda^{h}_{\underset{2}{|p}}\lambda^{p},$$

we conclude that the biholomorphically projective curves of the first kind and the biholomorphically projective curves of the second kind match, so we will simply call them the biholomorphically projective curves. Therefore, the biholomorphically projective curves of the spaces GR_N and $G\overline{R}_N$, respectively, satisfy relations [20]

$$\frac{d\lambda^{h}}{dt} + \Gamma^{h}_{pq}\lambda^{p}\lambda^{q} = a\lambda^{h} + bF^{h}_{p}\lambda^{p} + c\overset{2}{F}{}^{h}_{p}\lambda^{p}, \tag{8}$$

$$\frac{d\lambda^{h}}{dt} + \overline{\Gamma}^{h}_{pq}\lambda^{p}\lambda^{q} = \overline{a}\lambda^{h} + \overline{b}F^{h}_{p}\lambda^{p} + \overline{c}\overset{2}{F}{}^{h}_{p}\lambda^{p}, \tag{9}$$

where a, b, c, $\overline{a}$, $\overline{b}$ and $\overline{c}$ are functions of parameter t, $\lambda^i = \frac{dx^i}{dt}$, and Γ^h_{pq} and $\overline{\Gamma}^h_{pq}$ are connection coeficients of the spaces GR_N and $G\overline{R}_N$, respectively, $\overset{2}{F}{}^h_p = F^h_q F^q_p$.

From Equations (8) and (9) we obtain [20]

$$(\overline{\Gamma}^h_{pq} - \Gamma^h_{pq})\lambda^p\lambda^q = \psi\lambda^h + \sigma F^h_p\lambda^p + \tau\overset{2}{F}{}^h_p\lambda^p,$$

where we denote $\psi = \overline{a} - a, \sigma = \overline{b} - b, \tau = \overline{c} - c$. We can set $\psi = \psi_p\lambda^p, \sigma = \sigma_p\lambda^p, \tau = \tau_p\lambda^p$. Now, we have [20]

$$(\overline{\Gamma}^h_{pq} - \Gamma^h_{pq} - \psi_p\delta^h_q - \sigma_p F^h_q - \tau_p\overset{2}{F}{}^h_q)\lambda^p\lambda^q = 0.$$

From this we conclude that the following relation is satisfied [20]:

$$\overline{\Gamma}^h_{ij} = \Gamma^h_{ij} + \psi_{(i}\delta^h_{j)} + \sigma_{(i}F^h_{j)} + \tau_{(i}\overset{2}{F}{}^h_{j)} + \xi^h_{ij}, \tag{10}$$

and the deformation tensor has the form

$$P^h_{ij} = \psi_{(i}\delta^h_{j)} + \sigma_{(i}F^h_{j)} + \tau_{(i}\overset{2}{F}{}^h_{j)} + \xi^h_{ij}, \tag{11}$$

where (ij) is a symmetrization without division by indices i, j; ψ_i, σ_i and τ_i are vectors; $\overset{2}{F}{}^h_p = F^h_q F^q_p$ and ξ^h_{ij} is an antisymmetric tensor.

Inspired by the form of the deformation tensor (11), we will define a new type of mapping. Let GR_N and $G\overline{R}_N$ be two generalized Riemannian spaces with almost complex structures F^h_i and $\overline{F}^h_i$, respectively, where $F^h_i = \overline{F}^h_i$ in the common system of coordinates defined by the mapping $f : GR_N \to G\overline{R}_N$, and assume that it holds that $F^h_i \neq a\delta^h_i$, where a is scalar invariant.

The mapping $f : GR_N \to G\overline{R}_N$ is a quasi-canonical biholomorphically projective mapping if in the common coordinate system the connection coefficients Γ^h_{ij} and $\overline{\Gamma}^h_{ij}$ satisfy the relation

$$\overline{\Gamma}^h_{ij} = \Gamma^h_{ij} + \psi_{(i}\delta^h_{j)} + \tau_{(i}\overset{2}{F}{}^h_{j)} + \xi^h_{ij}, \tag{12}$$

where (ij) is a symmetrization without division by indices i, j; ψ_i and τ_i are vectors; $\overset{2}{F}{}^h_p = F^h_q F^q_p$ and ξ^h_{ij} is an antisymmetric tensor.

Let P^h_{ij} be a deformation tensor with respect to the quasi-canonical biholomorphically projective mapping $f : GR_N \to G\overline{R}_N$. Then, from (6) and (12), we have

$$P^h_{ij} = \psi_{(i}\delta^h_{j)} + \tau_{(i}\overset{2}{F}{}^h_{j)} + \xi^h_{ij}. \tag{13}$$

3. Some Relations between Curvature Tensors

In this section, we will find the relations between the corresponding curvature tensors of the spaces GR_N and $G\overline{R}_N$.

According to relations (5), (7) and (13), for the curvature tensor of the first kind we have

$$\begin{aligned}
\overline{R}^{i}_{1jmn} &= R^{i}_{1jmn} + \psi_{1j<n}\delta^{i}_{m>} + \psi_{1<m|n>}\delta^{i}_{j} + \psi_{p}\xi^{p}_{j<m}\delta^{i}_{n>} + 2\psi_{j}\xi^{i}_{mn} \\
&+ \tau_{j}\tau_{<n}\overset{4}{F}{}^{i}_{m>} + \tau_{m}\overset{2}{F}{}^{i}_{j|n} - \tau_{n}\overset{2}{F}{}^{i}_{j|m} + \tau_{j|<n}\overset{2}{F}{}^{i}_{m>} + \tau_{j}\overset{2}{F}{}^{i}_{<m|n>} + \tau_{<m|n>}\overset{2}{F}{}^{i}_{j} \\
&+ \tau_{p}\tau_{j}\overset{2}{F}{}^{p}_{<m}\overset{2}{F}{}^{i}_{n>} + \tau_{p}\tau_{<m}\overset{2}{F}{}^{i}_{n>}\overset{2}{F}{}^{p}_{j} + \xi^{p}_{jm}\xi^{i}_{pn} - \xi^{p}_{jn}\xi^{i}_{pm} + \xi^{i}_{j<m|n>} + \tau_{(p}\overset{2}{F}{}^{i}_{n)}\xi^{p}_{jm} \\
&+ \tau_{(j}\overset{2}{F}{}^{p}_{m)}\xi^{i}_{pn} - \tau_{(j}\overset{2}{F}{}^{p}_{n)}\xi^{i}_{pm} - \tau_{(p}\overset{2}{F}{}^{i}_{m)}\xi^{p}_{jn} + 2T^{p}_{mn}(\psi_{(j}\delta^{i}_{p)} + \tau_{(j}\overset{2}{F}{}^{i}_{p)} + \xi^{i}_{jp}),
\end{aligned} \tag{14}$$

where (ij) is a symmetrization without division , $< ij >$ is an antisymmetrization without division by indices i, j and

$$\begin{aligned}
&\overset{2}{F}{}^{h}_{j} = F^{h}_{p}F^{p}_{j},\ \overset{3}{F}{}^{h}_{j} = F^{h}_{p}F^{p}_{q}F^{q}_{j},\ \overset{4}{F}{}^{h}_{j} = F^{h}_{p}F^{p}_{q}F^{q}_{r}F^{r}_{j}, \\
&\psi_{1jn} = \psi_{1j|n} - \psi_{j}\psi_{n} - \psi_{p}\tau_{(j}\overset{2}{F}{}^{p}_{n)}.
\end{aligned} \tag{15}$$

Based on the facts given above, we have obtained the following statement.

Theorem 1. *A quasi-canonical biholomorphically projective relation between the curvature tensors of the first kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (14), where T^{h}_{ij} is the torsion tensor and the notation is the same as in (15).*

From relations (5), (7) and (13), for the curvature tensor of the second kind, we obtain the following:

$$\begin{aligned}
\overline{R}^{i}_{2jmn} &= R^{i}_{2jmn} + \psi_{2j<n}\delta^{i}_{m>} + \psi_{2<m|n>}\delta^{i}_{j} - \psi_{p}(\xi^{p}_{nj}\delta^{i}_{m} - \xi^{p}_{mj}\delta^{i}_{n}) \\
&+ 2\psi_{j}\xi^{i}_{nm} + \tau_{j}\tau_{<n}\overset{4}{F}{}^{i}_{m>} + \tau_{m}\overset{2}{F}{}^{i}_{j|n} - \tau_{n}\overset{2}{F}{}^{i}_{j|m} + \tau_{j|<n}\overset{2}{F}{}^{i}_{m>} \\
&+ \tau_{j}\overset{2}{F}{}^{i}_{<m|n>} + \tau_{<m|n>}\overset{2}{F}{}^{i}_{j} + \tau_{p}\tau_{j}\overset{2}{F}{}^{p}_{<m}\overset{2}{F}{}^{i}_{n>} + \tau_{p}\tau_{<m}\overset{2}{F}{}^{i}_{n>}\overset{2}{F}{}^{p}_{j} \\
&+ \tau_{(p}\overset{2}{F}{}^{i}_{n)}\xi^{p}_{mj} + \tau_{(j}\overset{2}{F}{}^{p}_{m)}\xi^{i}_{np} - \tau_{(j}\overset{2}{F}{}^{p}_{n)}\xi^{i}_{mp} - \tau_{(p}\overset{2}{F}{}^{i}_{m)}\xi^{p}_{nj} \\
&+ \xi^{p}_{mj}\xi^{i}_{np} - \xi^{p}_{nj}\xi^{i}_{mp} + \xi^{i}_{mj|n} - \xi^{i}_{nj|m} + 2T^{p}_{mn}(\psi_{(j}\delta^{i}_{p)} + \tau_{(j}\overset{2}{F}{}^{i}_{p)} + \xi^{i}_{pj}),
\end{aligned} \tag{16}$$

where $\overset{2}{F}{}^{h}_{j}$, $\overset{4}{F}{}^{h}_{j}$, are determined by Formula (15) and

$$\psi_{2jn} = \psi_{2j|n} - \psi_{j}\psi_{n} - \psi_{p}\tau_{(j}\overset{2}{F}{}^{p}_{n)}. \tag{17}$$

Therefore, the following theorem is valid.

Theorem 2. *A quasi-canonical biholomorphically projective relation between the curvature tensors of the second kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (16), where T^{h}_{ij} is the torsion tensor and the notation is the same as in (15) and (17).*

Considering relations (5), (7) and (13), for the curvature tensor of the third kind we have the following:

$$\begin{aligned}
\overset{3}{\overline{R}}{}^{i}_{jmn} &= \overset{3}{R}{}^{i}_{jmn} + \overset{2}{\psi}_{jn}\delta^{i}_{m} - \overset{1}{\psi}_{jm}\delta^{i}_{n} + (\overset{2}{\psi}_{m|n} - \overset{1}{\psi}_{n|m})\delta^{i}_{j} + 2\psi_{j}\xi^{i}_{nm} \\
&- \psi_{p}(\xi^{p}_{nj}\delta^{i}_{m} - \xi^{p}_{mj}\delta^{i}_{n}) + \tau_{j}\tau_{<n}\overset{4}{F}{}^{i}_{m>} + \tau_{m}\overset{2}{F}{}^{i}_{j|n} - \tau_{n}\overset{2}{F}{}^{i}_{j|m} \\
&+ \tau_{j|n}\overset{2}{F}{}^{i}_{m} - \tau_{j|m}\overset{2}{F}{}^{i}_{n} + \tau_{j}(\overset{2}{F}{}^{i}_{m|n} - \overset{2}{F}{}^{i}_{n|m}) + (\tau_{m|n} - \tau_{n|m})\overset{2}{F}{}^{i}_{j} \\
&+ \tau_{p}\tau_{j}\overset{2}{F}{}^{p}_{<m}\overset{2}{F}{}^{i}_{n>} + \tau_{p}\tau_{<m}\overset{2}{F}{}^{i}_{n>}\overset{2}{F}{}^{p}_{j} + \xi^{p}_{jm}\xi^{i}_{np} - \xi^{p}_{nj}\xi^{i}_{mp} - \xi^{i}_{jm|n} - \xi^{i}_{nj|m} \\
&+ \tau_{(p}\overset{2}{F}{}^{i}_{n)}\xi^{p}_{mj} + \tau_{(j}\overset{2}{F}{}^{p}_{m)}\xi^{i}_{np} - \tau_{(j}\overset{2}{F}{}^{p}_{n)}\xi^{i}_{pm} - \tau_{(p}\overset{2}{F}{}^{i}_{m)}\xi^{p}_{nj} \\
&+ 2(\psi_{(n}\delta^{p}_{m)} + \tau_{(n}\overset{2}{F}{}^{p}_{m)} + \xi^{p}_{nm})(T^{i}_{pj} + \xi^{i}_{pj}),
\end{aligned} \tag{18}$$

where the notation is the same as in (15) and (17).

In this way, the following theorem is proven.

Theorem 3. *A quasi-canonical biholomorphically projective relation between the curvature tensors of the third kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (18), where T^{h}_{ij} is the torsion tensor and the notation is the same as in (15) and (17).*

Using relations (5), (7) and (13), for a curvature tensor of the fourth kind we obtain the following:

$$\begin{aligned}
\overset{4}{\overline{R}}{}^{i}_{jmn} &= \overset{4}{R}{}^{i}_{jmn} + \overset{2}{\psi}_{jn}\delta^{i}_{m} - \overset{1}{\psi}_{jm}\delta^{i}_{n} + (\overset{2}{\psi}_{m|n} - \overset{1}{\psi}_{n|m})\delta^{i}_{j} + 2\psi_{j}\xi^{i}_{nm} \\
&- \psi_{p}(\xi^{p}_{nj}\delta^{i}_{m} - \xi^{p}_{mj}\delta^{i}_{n}) + \tau_{j}\tau_{<n}\overset{4}{F}{}^{i}_{m>} + \tau_{m}\overset{2}{F}{}^{i}_{j|n} - \tau_{n}\overset{2}{F}{}^{i}_{j|m} \\
&+ \tau_{j}(\overset{2}{F}{}^{i}_{m|n} - \overset{2}{F}{}^{i}_{n|m}) + \tau_{j|n}\overset{2}{F}{}^{i}_{m} - \tau_{j|m}\overset{2}{F}{}^{i}_{n} + (\tau_{m|n} - \tau_{n|m})\overset{2}{F}{}^{i}_{j} \\
&+ \tau_{p}\tau_{j}\overset{2}{F}{}^{p}_{<m}\overset{2}{F}{}^{i}_{n>} + \tau_{p}\tau_{<m}\overset{2}{F}{}^{i}_{n>}\overset{2}{F}{}^{p}_{j} + \xi^{p}_{jm}\xi^{i}_{np} - \xi^{p}_{nj}\xi^{i}_{mp} + \xi^{i}_{jm|n} - \xi^{i}_{nj|m} \\
&+ \tau_{(p}\overset{2}{F}{}^{i}_{n)}\xi^{p}_{mj} + \tau_{(j}\overset{2}{F}{}^{p}_{m)}\xi^{i}_{np} - \tau_{(j}\overset{2}{F}{}^{p}_{n)}\xi^{i}_{pm} - \tau_{(p}\overset{2}{F}{}^{i}_{m)}\xi^{p}_{nj} \\
&+ 2(\psi_{(n}\delta^{p}_{m)} + \tau_{(n}\overset{2}{F}{}^{p}_{m)} + \xi^{p}_{mn})(T^{i}_{pj} + \xi^{i}_{pj}),
\end{aligned} \tag{19}$$

where the notation is the same as in (15) and (17). This proves the next statement.

Theorem 4. *A quasi-canonical biholomorphically projective relation between the curvature tensors of the fourth kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (19), where T^{h}_{ij} is the torsion tensor and the notation is the same as in (15) and (17).*

Considering relations (5), (7) and (13), for the curvature tensor of the fifth kind we have the following:

$$\begin{aligned}
\overline{\underset{5}{R}}{}^{i}_{jmn} &= \underset{5}{R}{}^{i}_{jmn} + 2\psi_j T^i_{mn} + 2\psi_n T^i_{mj} + \frac{1}{2}(\underset{3}{\psi}_{jn} + \underset{4}{\psi}_{jn})\delta^i_m \\
&+ \frac{1}{2}(\underset{3}{\psi}_{<m|n>} + \underset{4}{\psi}_{<m|n>})\delta^i_j - \frac{1}{2}(\underset{3}{\psi}_{jm} + \underset{4}{\psi}_{jm})\delta^i_n \\
&+ \frac{1}{2}\overset{2}{F}{}^i_j(\underset{3}{\tau}_{<m|n>} + \underset{4}{\tau}_{<m|n>}) + \frac{1}{2}\overset{2}{F}{}^i_m(\underset{3}{\tau}_{j|n} + \underset{4}{\tau}_{j|n}) - \frac{1}{2}\overset{2}{F}{}^i_n(\underset{3}{\tau}_{j|m} + \underset{4}{\tau}_{j|m}) \\
&- \frac{1}{2}\tau_n(\underset{3}{\overset{2}{F}{}^i_{j|m}} + \underset{4}{\overset{2}{F}{}^i_{j|m}}) + \frac{1}{2}\tau_m(\underset{3}{\overset{2}{F}{}^i_{j|n}} + \underset{4}{\overset{2}{F}{}^i_{j|n}}) + \frac{1}{2}\tau_j(\underset{3}{\overset{2}{F}{}^i_{<m|n>}} + \underset{4}{\overset{2}{F}{}^i_{<m|n>}}) \\
&+ \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>} + \xi^p_{jm}\xi^i_{pn} - \xi^p_{jn}\xi^i_{mp} \\
&+ \frac{1}{2}(\underset{3}{\xi}{}^i_{jm|n} - \underset{3}{\xi}{}^i_{nj|m} - \underset{4}{\xi}{}^i_{jn|m} + \underset{4}{\xi}{}^i_{mj|n}),
\end{aligned} \tag{20}$$

where the notation is the same as in (15) and

$$\begin{aligned}
\underset{3}{\psi}_{jn} &= \underset{3}{\psi}_{j|n} - \psi_j\psi_n + \psi_p\tau_{(j}\overset{2}{F}{}^p_{n)}, \\
\underset{4}{\psi}_{jn} &= \underset{4}{\psi}_{j|n} - \psi_j\psi_n + \psi_p\tau_{(j}\overset{2}{F}{}^p_{n)}.
\end{aligned} \tag{21}$$

Based on the facts given above, we have proved the next theorem related to curvature tensors of the fifth kind.

Theorem 5. *A quasi-canonical biholomorphically projective relation between the curvature tensors of the fifth kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (20), where T^h_{ij} is the torsion tensor and the notation is the same as in (15) and (21).*

4. Equitorsion Quasi-Canonical Biholomorphically Projective Mapping

The mapping $f : GR_N \to G\overline{R}_N$ is an equitorsion quasi-canonical biholomorphically projective mapping,if the torsion tensors of the spaces GR_N and $G\overline{R}_N$ are equal in a common coordinate system after the mapping f. In this case, based on (6) and (13), we conclude that

$$\xi^h_{ij} = 0. \tag{22}$$

Then, relation (13) becomes

$$P^h_{ij} = \psi_{(i}\delta^h_{j)} + \tau_{(i}\overset{2}{F}{}^h_{j)}. \tag{23}$$

Considering (22), from (14), we obtain the following:

$$\begin{aligned}
\overline{\underset{1}{R}}{}^{i}_{jmn} &= \underset{1}{R}{}^{i}_{jmn} + \underset{1}{\psi}_{j<n}\delta^i_{m>} + \underset{1}{\psi}_{<m|n>}\delta^i_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>} \\
&+ \tau_m\underset{1}{\overset{2}{F}{}^i_{j|n}} - \tau_n\underset{1}{\overset{2}{F}{}^i_{j|m}} + \tau_{j|}\underset{1}{{}_{<n}}\overset{2}{F}{}^i_{m>} + \tau_j\underset{1}{\overset{2}{F}{}^i_{<m|n>}} + \tau_{<m|n>}\underset{1}{\overset{2}{F}{}^i_j} \\
&+ \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j + 2T^p_{mn}(\psi_{(j}\delta^i_{p)} + \tau_{(j}\overset{2}{F}{}^i_{p)}),
\end{aligned} \tag{24}$$

Hence, the next theorem holds.

Theorem 6. *An equitorsion quasi-canonical biholomorphically projective relation between the curvature tensors of the first kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (24), where T^h_{ij} is the torsion tensor and the notation is the same as in (15).*

The relation between the curvature tensors of the second kind (16), after applying relation (22), becomes the following:

$$\begin{aligned}\overline{R}^i_{2\,jmn} &= R^i_{2\,jmn} + \psi_{2\,j<n}\delta^i_{m>} + \psi_{2\,<m|n>}\delta^i_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>}\\ &+ \tau_m\overset{2}{F}{}^i_{2\,j|n} - \tau_n\overset{2}{F}{}^i_{2\,j|m} + \tau_{2\,j|<n}\overset{2}{F}{}^i_{m>} + \tau_j\overset{2}{F}{}^i_{2\,<m|n>} + \tau_{2\,<m|n>}\overset{2}{F}{}^i_j\\ &+ \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j + 2T^p_{mn}(\psi_{(j}\delta^i_{p)} + \tau_{(j}\overset{2}{F}{}^i_{p)} + \xi^i_{pj}).\end{aligned} \tag{25}$$

In this way, the following theorem is proven.

Theorem 7. *An equitorsion quasi-canonical biholomorphically projective relation between the curvature tensors of the second kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (25), where T^h_{ij} is the torsion tensor.*

The relation between the curvature tensors of the third kind (16), with respect to (22), becomes the following:

$$\begin{aligned}\overline{R}^i_{3\,jmn} &= R^i_{3\,jmn} + \psi_{2\,jn}\delta^i_m - \psi_{1\,jm}\delta^i_n + (\psi_{2\,m|n} - \psi_{1\,n|m})\delta^i_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>}\\ &+ \tau_m\overset{2}{F}{}^i_{2\,j|n} - \tau_n\overset{2}{F}{}^i_{1\,j|m} + \tau_{2\,j|n}\overset{2}{F}{}^i_m - \tau_{1\,j|m}\overset{2}{F}{}^i_n + \tau_j(\overset{2}{F}{}^i_{2\,m|n} - \overset{2}{F}{}^i_{1\,n|m})\\ &+ (\tau_{2\,m|n} - \tau_{1\,n|m})\overset{2}{F}{}^i_j + \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j\\ &+ 2(\psi_{(n}\delta^p_{m)} + \tau_{(n}\overset{2}{F}{}^p_{m)})T^i_{pj},\end{aligned} \tag{26}$$

and we may formulate the following theorem.

Theorem 8. *An equitorsion quasi-canonical biholomorphically projective relation between the curvature tensors of the third kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (26), where T^h_{ij} is the torsion tensor and the notation is the same as in (15) and (17).*

In particular, from relations (19) and (22), we have

$$\begin{aligned}\overline{R}^i_{4\,jmn} &= R^i_{4\,jmn} + \psi_{2\,jn}\delta^i_m - \psi_{1\,jm}\delta^i_n + (\psi_{2\,m|n} - \psi_{1\,n|m})\delta^i_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>}\\ &+ \tau_m\overset{2}{F}{}^i_{2\,j|n} - \tau_n\overset{2}{F}{}^i_{1\,j|m} + \tau_j(\overset{2}{F}{}^i_{2\,m|n} - \overset{2}{F}{}^i_{1\,n|m}) + \tau_{2\,j|n}\overset{2}{F}{}^i_m - \tau_{1\,j|m}\overset{2}{F}{}^i_n\\ &+ (\tau_{2\,m|n} - \tau_{1\,n|m})\overset{2}{F}{}^i_j + \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j\\ &+ 2(\psi_{(n}\delta^p_{m)} + \tau_{(n}\overset{2}{F}{}^p_{m)})T^i_{pj}.\end{aligned} \tag{27}$$

Therefore,the next theorem holds.

Theorem 9. *An equitorsion quasi-canonical biholomorphically projective relation between the curvature tensors of the fourth kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (27), where T^h_{ij} is the torsion tensor and the notation is the same as in (15) and (17).*

Analogously, from (20), with respect to (22), we obtain the following:

$$\begin{aligned}
&\overline{\underset{5}{R}}{}^i_{jmn} = \underset{5}{R}{}^i_{jmn} + 2\psi_j T^i_{mn} + 2\psi_n T^i_{mj} + \frac{1}{2}(\underset{3}{\psi}_{jn} + \underset{4}{\psi}_{jn})\delta^i_m \\
&+ \frac{1}{2}(\underset{3}{\psi}_{<m|n>} + \underset{4}{\psi}_{<m|n>})\delta^i_j - \frac{1}{2}(\underset{3}{\psi}_{jm} + \underset{4}{\psi}_{jm})\delta^i_n \\
&+ \frac{1}{2}\overset{2}{F}{}^i_j(\underset{3}{\tau}_{<m|n>} + \underset{4}{\tau}_{<m|n>}) + \frac{1}{2}\overset{2}{F}{}^i_m(\underset{3}{\tau}_{j|n} + \underset{4}{\tau}_{j|n}) - \frac{1}{2}\overset{2}{F}{}^i_n(\underset{3}{\tau}_{j|m} + \underset{4}{\tau}_{j|m}) \\
&- \frac{1}{2}\tau_n(\underset{3}{\overset{2}{F}}{}^i_{j|m} + \underset{4}{\overset{2}{F}}{}^i_{j|m}) + \frac{1}{2}\tau_m(\underset{3}{\overset{2}{F}}{}^i_{j|n} + \underset{4}{\overset{2}{F}}{}^i_{j|n}) + \frac{1}{2}\tau_j(\underset{3}{\overset{2}{F}}{}^i_{<m|n>} + \underset{4}{\overset{2}{F}}{}^i_{<m|n>}) \\
&+ \tau_p\tau_j\overset{2}{F}{}^p_{<m}\overset{2}{F}{}^i_{n>} + \tau_p\tau_{<m}\overset{2}{F}{}^i_{n>}\overset{2}{F}{}^p_j + \tau_j\tau_{<n}\overset{4}{F}{}^i_{m>},
\end{aligned} \tag{28}$$

i.e., the following theorem is valid:

Theorem 10. *An equitorsion quasi-canonical biholomorphically projective relation between the curvature tensors of the fifth kind of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ is given by Formula (28), where T^h_{ij} is the torsion tensor and the notation is the same as in (15) and (21).*

5. Invariant Geometric Objects of Quasi-Canonical Biholomorphically Projective Mappings

In this section, we will obtain an invariant geometric object of an equitorsion quasi-canonical biholomorphically projective mapping. In relation to that, in relation (23), let us set

$$\tau_i = \psi_p F^p_i.$$

Then, we have

$$\overline{\Gamma}{}^h_{ij} - \Gamma^h_{ij} = \psi_{(i}\delta^h_{j)} + \psi_p F^p_{(i}\overset{2}{F}{}^h_{j)}. \tag{29}$$

Contractingby indices h and i in (29), assuming that it is valid that

$$Tr(F^2) = 0, \text{ i.e., } \overset{2}{F}{}^p_p = F^p_q F^q_p = 0 \tag{30}$$

and

$$\overset{3}{F}{}^h_j = F^h_p F^p_q F^q_j = e\delta^h_j \ \ (e = \pm 1, 0), \tag{31}$$

we obtain

$$\psi_j = \frac{1}{N+1+e}(\overline{\Gamma}{}^p_{\underline{pj}} - \Gamma^p_{\underline{pj}}). \tag{32}$$

Substituting (32) in (29) we have

$$\begin{aligned}
&\overline{\Gamma}{}^h_{ij} - \frac{1}{N+1+e}\left(\overline{\Gamma}{}^p_{\underline{pi}}\delta^h_j + \overline{\Gamma}{}^p_{\underline{pj}}\delta^h_i + \overline{\Gamma}{}^q_{\underline{qp}}F^p_{(i}\overset{2}{F}{}^h_{j)}\right) \\
&= \Gamma^h_{ij} - \frac{1}{N+1+e}\left(\Gamma^p_{\underline{pi}}\delta^h_j + \Gamma^p_{\underline{pj}}\delta^h_i + \Gamma^q_{\underline{qp}}F^p_{(i}\overset{2}{F}{}^h_{j)}\right).
\end{aligned} \tag{33}$$

If we denote

$$\mathcal{QCT}^h_{ij} = \Gamma^h_{ij} - \frac{1}{N+1+e}\left(\Gamma^p_{\underline{pi}}\delta^h_j + \Gamma^p_{\underline{pj}}\delta^h_i + \Gamma^q_{\underline{qp}}F^p_{(i}\overset{2}{F}{}^h_{j)}\right), \tag{34}$$

relation (33) can be presented in the form

$$\overline{\mathcal{QCT}}{}^h_{ij} = \mathcal{QCT}^h_{ij}, \tag{35}$$

where $\overline{\mathcal{QCT}}^h_{ij}$ is an object of the space $G\overline{R}_N$. The magnitude $\mathcal{QCT}^h_{ij}$ is called a *Thomas equitorsion quasi-canonical biholomorphically projective parameter*and it is not a tensor.

Accordingly, we conclude that the following assertion is valid.

Theorem 11. *The geometric object $\mathcal{QCT}^h_{ij}$ given by Equation (34) is an invariant of the equitorsion quasi-canonical biholomorphically projective mapping $f : GR_N \to G\overline{R}_N$, provided that relations (30) and (31) are valid.*

6. Discussion

This paper is a continuation of the research discussed in paper [20]. The form of the deformation tensor of a biholomorphically projective mapping allows us to define new types of mappings. Here, we have defined quasi-canonical biholomorphically projective mappings and equitorsion quasi-canonical biholomorphically projective mappings. Also, we obtained some relations between the corresponding curvature tensors of the generalized Riemannian spaces GR_N and $G\overline{R}_N$ and we found an invariant geometric object of an equitorsion quasi-canonical biholomorphically projective mapping which is of the Thomas type. Apart from the mapping defined in this paper, it is possible to consider some other types of mapping, which will be the subject of our further research. Also, the goal of further research will be to find new invariant geometric objects. The findings of this paper also motivate us to answer the following questions: (i) Are there any interpretations from a physical point of view? (ii) What is the geometrical significance?

Author Contributions: Both authors have equally contributed to this work. Both authors wrote, read, and approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: V.M.M. acknowledges the grant of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia 451-03-65/2024-03/200133 for carrying out this research. M.S.S. acknowledges the grant of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia 451-03-65/2024-03/200124 for carrying out this research.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the referees for their valuable comments which helped to improve the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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