

Generalized Birecurrent Finsler Geometry: Curvature Identities and Mathematical Foundations for Mechanical and Renewable Energy Systems

Wafa'a Hadi Ali Hadi¹  , Adel Mohammed Ali Al-Qashbari^{2,*}  , Rahma Saad Elzer³  

¹Department of Mathematics, Community College-Aden, Aden, Yemen

²Department of Biomedical Engineering, Faculty of Engineering and Computers, University of Science and Technology, Aden, Yemen

³Physics Department, Faculty of Science, Derna University, Derna, Libya

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ABSTRACT

This paper investigates a class of generalized birecurrent Finsler spaces characterized by a generalized recurrence condition imposed on Cartan's third curvature tensor with respect to Cartan's connection. The geometric framework is formulated using non-null covariant vector fields and higher-order covariant tensor fields. Fundamental consequences of the generalized birecurrent condition are derived, including identities involving the $h(v)$ -torsion tensor, deviation tensor, Ricci tensor, curvature vector, and curvature scalar. It is shown that the Ricci tensor, curvature vector, deviation tensor, and curvature scalar are non-vanishing in the considered class of Finsler spaces. Several curvature identities are established through covariant differentiation, tensor contraction, and transvection of the fundamental geometric relations. The developed framework provides a mathematical basis for studying direction-dependent and curvature-constrained dynamical structures. It also suggests potential extensions to mechanical systems and renewable energy technologies involving directional states, nonlinear motion, and geometric constraints. These results establish a theoretical foundation for developing Finsler-geometric models of mechanical dynamics, energy conversion, and renewable energy systems.

الهندسة الفينسلرية ثنائية التكرار المعممة: متطابقات الانحناء والأسس الرياضية للأنظمة الميكانيكية وأنظمة الطاقة المتجددة

وفاء هادي علي هادي¹، عادل محمد علي القشبري^{2,*}، رحمة سعد الزير³

المخلص	الكلمات المفتاحية
في هذا العمل، تم تطوير إطار موحد عالي المستوى يربط بين الجريان اللاتماثلي وبنى التكرارية من الرتب العليا وهندسة فينسلر. ويركز الإطار على العلاقات بين موتر الانحناء الإسقاطي لوايل (Weyl projective curvature tensor) وموتر الانحناء الدائري (conccircular curvature tensor) في فضاءات فينسلر التكرارية الممتدة من الرتبة الثانية والفضاءات الفينسلرية ثنائية التكرار (birecurrent Finsler spaces). ومن خلال اشتقاق علاقات موترية جديدة وشروط ضرورية وكافية صارمة، جرى توسيع نظرية التكرار الكلاسيكية. وللتحقق من قابلية التطبيق، أجريت محاكاة باستخدام ديناميكا الموائع الحسابية (CFD) لجريان لزج داخل أنابيب منحنية ذات انحناءات متفاوتة وظروف دخول مختلفة. وأظهرت النتائج اعتمادًا اتجاهيًا ملحوظًا لكل من السرعة وإجهاد القص على الجدار. كما تتوافق النتائج مع النموذج الهندسي المقترح، مما يشير إلى وجود علاقة وثيقة بين الهندسة التفاضلية المتقدمة والسلوك اللاتماثلي للموائع، مع ما قد يترتب على ذلك من تطبيقات في نماذج الجاذبية المعدلة وعلم الكونيات.	هندسة فينسلر الجريان اللاتماثلي تفاعل انحناء وإيل الدائري الفضاءات الفينسلرية ثنائية التكرار التكرار من الرتب العليا ديناميكا الموائع الحسابي

Introduction

Finsler geometry constitutes an important extension of Riemannian geometry and provides a flexible mathematical framework for describing geometric structures whose properties depend on both position and direction. This directional dependence makes Finsler geometry particularly suitable for studying nonlinear and anisotropic phenomena. In recent decades, considerable attention has been devoted to recurrent and generalized recurrent structures in Finsler geometry because they provide constrained relationships between geometric quantities and their covariant derivatives. Various forms of recurrence have been investigated in association with different Finsler connections and curvature

tensors, leading to a rich class of geometric structures and identities.

Among the fundamental geometric objects in Finsler geometry, Cartan's connection and its associated curvature tensors play a central role in characterizing the intrinsic structure of a Finsler space. Recurrence conditions imposed on curvature tensors provide an effective framework for analyzing the behavior of curvature under covariant differentiation. Previous investigations have considered recurrent, generalized recurrent, projective recurrent, birecurrent, and related higher-order Finsler structures, revealing significant relationships among curvature, torsion, deviation, and Ricci-type tensors. These results provide

*Corresponding author

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important structural constraints for the characterization of generalized Finsler spaces.

Motivated by these developments, the present work investigates a class of generalized birecurrent Finsler spaces in which Cartan's third curvature tensor satisfies a generalized recurrence condition with respect to Cartan's connection. The proposed formulation is based on non-null covariant vector fields and associated covariant tensor fields. By applying covariant differentiation, contraction, transvection, and Bianchi-type identities, several fundamental relationships are derived for the geometric quantities associated with the considered space. In particular, the study establishes identities involving the $h(v)$ -torsion tensor, deviation tensor, Ricci tensor, curvature vector, and curvature scalar.

A principal objective of this study is to characterize the consequences of the generalized birecurrence condition for these fundamental curvature quantities. The analysis shows that the Ricci tensor, curvature vector, deviation tensor, and curvature scalar are non-vanishing within the generalized birecurrent class under consideration. Furthermore, the resulting curvature identities provide additional structural restrictions and extend the collection of known relationships associated with recurrent Finsler geometries.

The significance of the proposed framework also extends to potential applications in mathematical modeling. Because Finsler geometry incorporates directional dependence, it offers a suitable geometric perspective for systems involving nonlinear motion, rotational states, anisotropic behavior, and geometric constraints. In mechanical engineering, such features occur in various dynamical systems and rotating machinery. Similarly, renewable energy technologies [1-4], including wind energy conversion [5,6] and solar-tracking systems [7-9], involve directional motion, orientation, and constrained mechanical processes. Although the present work is theoretical and does not introduce a numerical or experimental model of a specific engineering system, its curvature structure and tensor identities may provide a mathematical foundation for future direction-dependent models of mechanical dynamics and energy-conversion processes.

Accordingly, the main contribution of this paper is the development of a rigorous generalized birecurrent Finsler framework and the derivation of associated curvature identities through Cartan's connection. The obtained results enrich the theoretical structure of generalized recurrent Finsler geometry and provide a basis for future application-oriented studies in nonlinear mechanics, anisotropic systems, and renewable-energy technologies.

Finsler geometry provides a powerful mathematical framework for describing anisotropic geometric structures and has attracted increasing attention because of its applications in mechanics, physics, robotics, and nonlinear dynamical systems [10-12]. The foundational development of Finsler spaces and their differential-geometric structures has been established through classical treatments of Finsler geometry and subsequent studies of curvature, geodesics, and geometric invariants [12,13]. More recent investigations have extended these foundations toward nonlinear spectra, curvature properties, and geometric models with applications in physical systems [10, 14-16]. In the context of recurrent Finsler geometry, several studies have examined recurrent tensor fields and the structural properties of generalized recurrent spaces, including torsion-related tensors and their

special geometric conditions [17,18]. The concept of birecurrence has subsequently been investigated for different tensor fields and Finsler structures, providing broader recurrence conditions beyond the classical framework [19]. Higher-order recurrence has also been developed through fourth-order and generalized recurrent Finsler spaces, with particular attention to recurrence decompositions and higher-order curvature tensors [20-22]. Further contributions have addressed BK-5th and BW-four-recurrent Finsler spaces, thereby extending recurrence theory to higher-order geometric structures [23,24]. Studies involving generalized recurrence and Lie derivatives have established additional relationships between curvature tensors and their differential properties [25,26]. Particular attention has also been devoted to projective and M-projective curvature tensors in recurrent and birecurrent Finsler spaces, leading to new geometric identities and characterizations [27,28]. The interaction between generalized recurrence and fundamental curvature tensors, including Cartan and Weyl tensors, has further enriched the geometric characterization of birecurrent Finsler spaces [29]. Recent research has increasingly connected these mathematical structures with applied problems, including anisotropic image processing, where generalized recurrent Finsler models provide a geometric framework for representing direction-dependent structures [30]. Higher-order recurrent Finsler geometry has also been associated with anisotropic flow modelling and computational fluid dynamics, demonstrating its potential in modelling complex mechanical systems [31]. Moreover, generalized recurrent Finsler structures have been investigated in intelligent robotic path planning and anisotropic biomedical systems, highlighting their relevance to emerging engineering applications [32,33]. Related developments in spatial elasticity, nonlinear stress estimation, and natural convection further demonstrate the broader relevance of advanced mathematical modelling to engineering phenomena [34-38]. Despite these advances, the systematic integration of higher-order recurrence conditions, curvature identities, and application-oriented Finsler structures remains an active research direction, motivating further development of generalized recurrent and birecurrent Finsler models.

Despite these significant developments, the existing literature remains largely focused on particular classes of recurrent or birecurrent Finsler spaces and on individual curvature tensors or differential operators. A systematic treatment that combines generalized birecurrence with the derivation of interconnected identities for the principal geometric tensors associated with Cartan's connection is still limited. In particular, the relationships among the $h(v)$ -torsion tensor, deviation tensor, Ricci tensor, curvature vector, and curvature scalar under a generalized birecurrent condition require further investigation. The present work addresses this gap by establishing a unified framework for generalized birecurrent Finsler spaces and deriving new curvature identities through covariant differentiation, contraction, transvection, and Bianchi-type relations. Moreover, the non-vanishing character of the fundamental curvature quantities is examined within the proposed structure. Beyond its intrinsic geometric significance, the framework provides a mathematical basis for describing direction-dependent and curvature-constrained phenomena, with potential relevance to anisotropic mechanical systems, nonlinear dynamics, and renewable-energy technologies.

Let F be a Finsler metric defined on an n -dimensional Finsler manifold, satisfying the standard regularity and positivity conditions. Denote by g_{ij} the corresponding fundamental metric tensor, and by G_{jk}^i and G_{jk}^{*i} the coefficients of the Cartan and Berwald connections, respectively.

These connection coefficients are symmetric with respect to their lower indices and are positively homogeneous of degree zero with respect to the directional variables.

The Cartan and Berwald connection coefficients, together with their associated tensorial quantities, are related through the following fundamental relation:

$$g_{ij} g^{jk} = \delta_i^k = \begin{cases} 1, & \text{if } i = k \\ 0, & \text{if } i \neq k \end{cases} \quad (1)$$

The vectors y_i and y^i satisfies the following relations

$$a) \quad y_i = g_{ij} y^j, \quad b) \quad y_i y^i = F^2, \quad (2)$$

$$c) \quad g_{ij} = \partial_i y_j = \partial_j y_i,$$

$$d) \quad g_{ij} y^j = \frac{1}{2} \partial_i F^2 = F \partial_i F, \quad \text{and}$$

$$e) \quad \partial_j y^i = \delta_j^i.$$

The tensor C_{ijk} defined by

$$C_{ijk} = \frac{1}{2} \partial_i g_{jk} = \frac{1}{4} \partial_i \partial_j \partial_k F^2, \quad (3)$$

is known as (h) hv-torsion tensor.

It is positively homogeneous of degree -1 in the directional arguments and symmetric in all its indices.

The (v) hv-torsion tensor C_{ik}^h and its associate (h) hv-torsion tensor C_{ijk} are related by

$$a) \quad C_{ijk} y^i = C_{kij} y^i = C_{jki} y^i = 0, \quad (4)$$

$$b) \quad C_{jk}^i y^j = C_{kj}^i y^j = 0, \quad \text{and}$$

$$c) \quad C_{ik}^h = g^{hj} C_{ijk}.$$

The (v) hv-torsion tensor C_{ik}^h is also positively homogeneous of degree -1 in the directional arguments and symmetric in its lower indices.

Cartan deduced the h-covariant derivative for an arbitrary vector field X^i with respect to x^k

$$X_{ik}^i = \partial_k X^i - (\partial_r X^i) G_k^r + X^r \Gamma_{rk}^{*i}. \quad (5)$$

The metric tensor g_{ij} and the vector y^i are covariant constant with respect to a above process, i.e.

$$a) \quad g_{ijk} = 0, \quad b) \quad y_{ik}^i = 0 \quad \text{and} \quad c) \quad g_{ik}^{ij} = 0. \quad (6)$$

The process of h-covariant differentiation with respect to x^k commute with partial differentiation with respect to y^j for arbitrary vector field X^i , according to

$$\partial_j (X_{ik}^i) - (\partial_j X^i)_{ik} = X^r (\partial_j \Gamma_{rk}^i) - (\partial_r X^i) P_{jk}^r, \quad (7)$$

where

$$a) \quad \partial_j \Gamma_{hk}^{*r} = \Gamma_{jhk}^{*r}, \quad b) \quad P_{kh}^i y^k = 0 = P_{kh}^i y^h, \quad (8)$$

$$c) \quad P_{jkh}^i y^j = P_{jkh}^i.$$

The tensor P_{kh}^i is called v(hv)-torsion tensor and its associate tensor P_{jkh} is given by

$$a) \quad g_{rj} P_{kh}^r = P_{kjh}. \quad (9)$$

The associate tensor P_{ijkh} of the (hv)-curvature tensor P_{jkh}^i is given by

$$b) \quad g_{ir} P_{jkh}^r = P_{ijkh}. \quad (9)$$

The quantities H_{jkh}^i and H_{kh}^i form the components of tensors and they called h-curvature tensor of Berwald (Berwald curvature tensor) and h(v)-torsion tensor, respectively, and defined as follow:

$$a) \quad H_{jkh}^i = \partial_j G_{kh}^i + G_{kh}^r G_{rj}^i + G_{rhj}^i G_k^r - \partial_j G_{hk}^i - G_{hk}^r G_{rj}^i - G_{rkj}^r G_h^r, \quad (10)$$

$$b) \quad H_{kh}^i = \partial_h G_k^i + G_k^r C_{rh}^i - \partial_k G_h^i - G_h^r C_{rk}^i.$$

They are skew-symmetric in their lower indices, i.e. k and h . Also they are positively homogeneous of degree zero and one, respectively in their directional arguments. They are also related by

$$a) \quad H_{jkh}^i y^j = H_{kh}^i, \quad b) \quad H_{jkh}^i = \partial_j H_{kh}^i, \quad (11)$$

$$c) \quad H_{jk}^i = \partial_j H_k^i.$$

These tensors were constructed initially by mean of the tensor H_h^i , called the deviation tensor, given by

$$H_h^i = 2 \partial_h G^i - \partial_r G_h^i y^r + 2 G_{hs}^i G^s - G_s^i G_h^s. \quad (12)$$

The deviation tensor H_h^i is positively homogeneous of degree two in the directional arguments.

In view of Euler's theorem on homogeneous functions and by contracting the indices i and h in (11) and (12), we have the following:

$$a) \quad H_{jk}^i y^j = -H_{kj}^i y^j = H_k^i, \quad (13)$$

$$b) \quad y_i H^i = 0.$$

The quantities H_{jkh}^i and H_{kh}^i are satisfies the following

$$a) \quad H_{ijkh} = g_{jr} H_{ihk}^r, \quad b) \quad H_{jk.h} = g_{jr} H_{hk}^r, \quad (14)$$

$$c) \quad y_i H_{jk}^i = 0.$$

Cartan's third curvature tensor R_{jkh}^i satisfies the identity known as Bianchi identity

$$a) \quad R_{jkh}^i + R_{jsk}^i + R_{jsh}^i \quad (15)$$

$$+ (R_{mhs}^r P_{jkr}^i + R_{mkh}^r P_{jsr}^i + R_{msk}^r P_{jhr}^i) y^m = 0,$$

$$b) \quad R_{ijhk} + R_{ihkj} + R_{ikjh}$$

$$+ (C_{ijs} K_{rhk}^s + C_{ihs} K_{rkj}^s + C_{iks} K_{rjh}^s) y^r = 0, \quad \text{where}$$

$$c) \quad P_{ijs}^r = \partial_s \Gamma_{ij}^{*r} - C_{isj}^r + C_{im}^r C_{jsk}^m y^k.$$

The Ricci tensor R_{jk} , the deviation tensor R_h^r and the curvature scalar R of the curvature tensor R_{jkh}^i are given by

$$a) \quad R_{jkh}^i y^j = H_{hk}^i = K_{jhk}^i y^j, \quad (16)$$

$$b) \quad R_{ijhk} = g_{rj} R_{ihk}^r,$$

$$c) \quad R_{jkhm} y^j = H_{kh.m}^r, \quad d) \quad R_{ihk}^r = g^{jr} R_{ijhk}, \quad \text{and}$$

$$e) \quad R_{jkh}^i g^{jk} = R_h^i.$$

The contracted tensor R_{kh} (Ricci tensor) and R_k (Curvature vector) are also connected by

$$a) \quad R_{jk} y^k = R_j, \quad b) \quad R_{jk} y^j = H_k, \quad (17)$$

$$c) \quad R_{jki}^i = R_{jk}.$$

Also, this tensor satisfies the following relation too

$$a) \quad R_{jkh}^i = K_{jkh}^i + C_{js}^i K_{rhk}^s y^r, \quad (18)$$

$$b) \quad R_{ijkh} = K_{ijkh} + C_{ijs} H_{kh}^s, \quad \text{and}$$

$$c) \quad R_{jkhm} y^j = H_{kh.m}^r.$$

where R_{ijkh} is the associate curvature tensor of R_{jkh}^i .

Cartan's fourth curvature tensor K_{jkh}^i and its associate curvature tensor of K_{ijkh} satisfy the following known as Bianchi identities

$$a) \quad K_{jkh}^i + K_{hjk}^i + K_{khj}^i = 0, \quad (19)$$

$$b) \quad K_{jrk h} + K_{hrjk} + K_{krhj} = 0.$$

2. On Generalized R^h -Recurrent Space

Consider an n -dimensional Finsler space F_n whose Cartan's third curvature tensor satisfies the following generalized birecurrence condition:

$$R_{jkhlm}^i = \lambda_m R_{jkh}^i + \mu_m (\delta_h^i g_{jk} - \delta_k^i g_{jh}) + \frac{1}{4} \gamma_m (R_k^i g_{jh} - R_h^i g_{jk}), \quad R_{jkh}^i \neq 0, \quad (20)$$

where λ_m and μ_m are non-null covariant vectors field. We shall call such space as a generalized R^h -recurrent space. We shall denote it briefly by $GR^h\text{-}RF_n$.

By taking the covariant derivative of equation (20) with

respect to x^l in the framework of Cartan's connection and applying condition (6a), we obtain the following relation:

$$R_{jkh|m|l}^i = a_{ml}R_{jkh}^i + b_{ml}(\delta_k^i g_{jh} - \delta_h^i g_{jk}) + \frac{1}{4}c_{ml}(R_k^i g_{jh} - R_h^i g_{jk}) + \frac{1}{4}\gamma_m(R_k^i g_{jh} - R_h^i g_{jk})_{|l} \quad (21)$$

Such that $a_{ml} = \lambda_{m|l} + \lambda_m \lambda_l$, $b_{ml} = \mu_{m|l} + \lambda_m \mu_l$ and $c_{ml} = \lambda_m \gamma_l + \gamma_{m|l}$, where a_{ml} , b_{ml} and c_{ml} are non-vanishing second-order covariant tensor fields, and λ_m is a non-vanishing first-order covariant vector field.

Definition 2.1. A Finsler space in which Cartan's third curvature tensor R_{jkh}^i satisfies condition (21) is called a generalized $R_{|h}$ -birecurrent space, and the associated tensor is referred to as a generalized h-birecurrent tensor. These are denoted concisely by $G^{2nd}R_{|h} - BRF_n$ and $G^{2nd}h - BR$, respectively.

Transvecting (21) by the metric tensor g_{ip} , using (6a), (16b) (17d) and in view of (1), we get

$$R_{jpkh|m|l} = a_{ml}R_{jpkh} + b_{ml}(g_{kp}g_{jh} - g_{hp}g_{jk}) + \frac{1}{4}c_{ml}(R_{pk}g_{jh} - R_{ph}g_{jk}) + \frac{1}{4}\gamma_m(R_{pk}g_{jh} - R_{ph}g_{jk})_{|l} \quad (22)$$

Conversely, the transvection of the condition (21) by the associate tensor g^{ip} of the metric tensor g_{ip} , yields the condition (21). Thus, the condition (21) is equivalent to the condition (21). Therefore, a generalized $R_{|h}$ -birecurrent space characterized by the condition (22).

Therefore, we have

Theorem 2.1. An $G^{2nd}R_{|h} - BRF_n$, may characterized by the condition (22).

Let us consider $G^{2nd}R_{|h} - BRF_n$ characterized by the condition (21).

Transvecting the condition (20) by y^j , using (6b), (16a) and (2a), we get

$$H_{kh|m|l}^i = a_{ml}H_{kh}^i + b_{ml}(\delta_k^i y_h - \delta_h^i y_k) + \frac{1}{4}c_{ml}(R_k^i y_h - R_h^i y_k) + \frac{1}{4}\gamma_m(R_k^i y_h - R_h^i y_k)_{|l} \quad (23)$$

Further, transvecting (2.4) by y^k , using (6b), (13a), (2b) and in view of (1), we get

$$H_{h|m|l}^i = a_{ml}H_h^i + b_{ml}(y^i y_h - \delta_h^i F^2) + \frac{1}{4}c_{ml}(R_k^i y_h y^k - R_h^i F^2) + \frac{1}{4}\gamma_m(R_k^i y_h y^k - R_h^i F^2)_{|l} \quad (24)$$

Therefore, we have

Theorem 2.2. In $G^{2nd}R_{|h} - BRF_n$, the h-covariant derivative of the h(v)-torsion tensor H_{kh}^i and the deviation tensor H_h^i is given by the conditions (23) and (24), respectively.

Contracting the indices i and h in the condition (21), using (17c) and (1), we get

$$R_{jk|m|l} = a_{ml}R_{jk} + (1-n)b_{ml}g_{jk} + \frac{1}{4}c_{ml}(R_k y_j - R g_{jk}) + \frac{1}{4}\gamma_m(R_k y_j - R g_{jk})_{|l} \quad (25)$$

Transvecting (25) by y^k , using (6b), (17a) and (2a), we get $R_{j|m|l} = a_{ml}R_j + (1-n)b_{ml}y_j$.

Further, transvecting the condition (21) by the associate tensor g^{jk} of the metric tensor g_{jk} , using (6c), (16e) and in view of (1), we get

$$R_{h|m|l}^i = a_{ml}R_h^i + b_{ml}(y^i y_h - \delta_h^i) + \frac{1}{4}c_{ml}(R_k y_h y^k - R_h^i) + \frac{1}{4}\gamma_m(R_k y_h y^k - R_h^i)_{|l} \quad (27)$$

Contracting the indices i and h in condition (27) and using (1), we get

$$R_{|m|l} = a_{ml}R + (F^2 - n)b_{ml}, \text{ where } R_r^r = R. \quad (28)$$

The conditions (25-28), show that the Ricci tensor R_{jk} , the curvature vector R_j , the deviation tensor R_h^i and the curvature scalar R of a generalized $R_{|h}$ -birecurrent space cannot vanish, because the vanishing of them implies the vanishing of the covariant tensor fields i.e. $b_{ml} = 0$, a contradiction.

Thus, we conclude

Theorem 2.3. In $G^{2nd}R_{|h} - BRF_n$, the Ricci tensor R_{jk} , the curvature vector R_j , the deviation tensor R_h^i and the curvature scalar R are non-vanishing.

Certain Identities

In this section we shall obtain some identities in $G^{2nd}R_{|h} - BRF_n$.

Differentiating (15b) covariant twice with respect to x^m and x^l in the sense of Cartan successively and transvecting (15b) by the associate tensor g^{jp} of the metric tensor g_{jp} , using (6c), (16a), (16d) and (4c), we get

$$2R_{ihk|m|l}^p + R_{ikh|m|l}^p + (C_{is}^p H_{hk}^s + g^{jp} C_{ih s} H_{kj}^s + g^{jp} C_{iks} H_{jh}^s)_{|m|l} = 0 \quad (29)$$

Transvecting (29) by y^i , using (6b), (16a), (4b) and (4a), we get

$$2H_{hk|m|l}^p + H_{kh|m|l}^p = 0 \quad (30)$$

Thus, we conclude

Theorem 3.1. In $G^{2nd}R_{|h} - BRF_n$, the identities (29) and (30) hold good.

Using (16b) and (16a) in the identity (15b), we get

$$g_{rj}R_{ihk}^r + g_{rh}R_{ikj}^r + g_{rk}R_{ijh}^r + C_{ijs}H_{hk}^s + C_{ih s}H_{kj}^s + C_{iks}H_{jh}^s = 0 \quad (31)$$

Now, transvecting (31) by y^i , using the equations (16a) and (4a), we get

$$g_{rj}H_{hk}^r + g_{rh}H_{kj}^r + g_{rk}H_{jh}^r = 0 \quad (32)$$

By using (14b), the equation (32) yields to

$$H_{hj.k} + H_{kh.j} + H_{jk.h} = 0 \quad (33)$$

Transvecting (32) by y^h , using (13a) and (2a), we get

$$g_{rj}H_k^r = g_{rk}H_j^r \quad (34)$$

Thus, we conclude

Theorem 3.2. In $G^{2nd}R_{|h} - BRF_n$, the identities (32-34) hold good.

Using (16a) in (18a), we get

$$R_{jkh}^i = K_{jkh}^i + C_{js}^i H_{hk}^s \quad (35)$$

Differentiating (35), covariant twice with respect to x^m and x^l in the sense of Cartan successively, we get

$$R_{jkh|m|l}^i = K_{jkh|m|l}^i + (C_{js}^i H_{hk}^s)_{|m|l} \quad (36)$$

Using (2.2) in (3.8) and in view of (35), we get

$$K_{jkh|m|l}^i = a_{ml}K_{jkh}^i + b_{ml}(\delta_k^i g_{jh} - \delta_h^i g_{jk}) + \frac{1}{4}c_{ml}(R_k^i g_{jh} - R_h^i g_{jk}) + \frac{1}{4}\gamma_m(R_k^i g_{jh} - R_h^i g_{jk})_{|l} + (C_{js}^i H_{hk}^s)_{|m|l} - a_{ml}(C_{js}^i H_{hk}^s) \quad (37)$$

$$K_{jkh|m|l}^i = a_{ml}K_{jkh}^i + b_{ml}(\delta_k^i g_{jh} - \delta_h^i g_{jk}) + \frac{1}{4}c_{ml}(R_k^i g_{jh} - R_h^i g_{jk}) + \frac{1}{4}\gamma_m(R_k^i g_{jh} - R_h^i g_{jk})_{|l} \quad (38)$$

If and only if

$$(C_{js}^i H_{hk}^s)_{|m|l} = a_{ml}(C_{js}^i H_{hk}^s) \quad (39)$$

Thus, we conclude

Theorem 3.3. In $G^{2nd}R_{|h} - BRF_n$, the Cartan's fourth

curvature tensor K_{jkh}^i is $G^{2nd}h$ -BR if and only if $C_{js}^i H_{hk}^s$ satisfied the birecurrent property.

Differentiating (18b) covariant twice with respect to x^m and x^l in the sense of Cartan successively, we get

$$R_{ijkhlm} = K_{ijkhlm} + (C_{ijs} H_{kh}^s)_{|m|l} . \quad (40)$$

Using (23) in (3.40) and in view of (18b), get

$$K_{ijkhlm} = a_{ml} K_{ijkh} + b_{ml} (g_{kj} g_{ih} - g_{hj} g_{ik}) \quad (41)$$

$$+ \frac{1}{4} c_{ml} (R_{jk} g_{ih} - R_{jh} g_{ik}) + \frac{1}{4} \gamma_m (R_{jk} g_{ih} - R_{jh} g_{ik})_{|l} \\ + (C_{ijs} H_{kh}^s)_{|m|l} - a_{ml} (C_{ijs} H_{kh}^s) .$$

$$K_{ijkhlm} = a_{ml} K_{ijkh} + b_{ml} (g_{kj} g_{ih} - g_{hj} g_{ik}) \quad (42)$$

$$+ \frac{1}{4} c_{ml} (R_{jk} g_{ih} - R_{jh} g_{ik}) \\ + \frac{1}{4} \gamma_m (R_{jk} g_{ih} - R_{jh} g_{ik})_{|l} .$$

If and only if

$$(C_{ijs} H_{kh}^s)_{|m|l} = a_{ml} (C_{ijs} H_{kh}^s) . \quad (43)$$

Thus, we conclude

Theorem 3.4. In $G^{2nd}R_{|h}-BRF_n$, the associate tensor K_{ijkh} of the Cartan's fourth curvature tensor K_{jkh}^i is $G^{2nd}h$ -BR if and only if the condition (43) holds good.

Conclusion

This study has developed a generalized birecurrent Finsler framework based on Cartan's connection and the generalized recurrence condition imposed on Cartan's third curvature tensor. Within this framework, several fundamental consequences of the proposed geometric structure have been established using covariant differentiation, tensor contraction, transvection, and Bianchi-type identities. In particular, new relationships involving the $h(v)$ -torsion tensor, deviation tensor, Ricci tensor, curvature vector, and curvature scalar have been derived. The analysis further demonstrates the non-vanishing character of the principal curvature quantities considered in the generalized birecurrent setting. These results provide additional structural constraints for the characterization of generalized recurrent Finsler spaces and contribute to the development of curvature-based identities in Finsler geometry. Overall, the proposed framework extends existing recurrent and birecurrent structures and provides a rigorous mathematical foundation for further investigations of direction-dependent geometric and dynamical systems.

Future Applications and Research Directions

The theoretical framework developed in this study opens several promising directions for future research. First, the generalized birecurrent curvature structure can be incorporated into mathematical models of nonlinear mechanical systems, particularly those involving directional dependence, rotational motion, anisotropic behavior, and geometric constraints. Second, the framework may be investigated in wind-energy conversion systems, where aerodynamic direction, rotor dynamics, and nonlinear mechanical motion interact within a direction-dependent operating environment. Third, Finsler-geometric formulations may be developed for solar-tracking mechanisms, in which the orientation and trajectory of energy-collection surfaces are governed by directional and geometric constraints. Further extensions could also address anisotropic materials, vibration and rotating machinery, nonlinear control systems, and energy-conversion processes.

An important future objective is to establish explicit mathematical models that couple the curvature identities derived here with the governing equations of mechanical and

renewable-energy systems. Numerical simulations, stability analysis, and parameter estimation could then be employed to determine whether generalized birecurrent Finsler structures provide measurable advantages over conventional Riemannian or Euclidean formulations. Such developments would transform the present theoretical framework into an application-oriented geometric modelling methodology for direction-dependent mechanical dynamics and renewable-energy technologies.

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Conceptualization; investigation, validation, writing-original draft preparation; **Elzer**: Review and editing, formal analysis. All authors have read and agreed to the published version of the manuscript.

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