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Original Article

Concircular Curvature Tensor on N(k)-Contact Metric Manifolds with Respect to Semi-Symmetric Non-Metric Connection

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Abstract - *In the present paper, we study N(k)-contact metric manifolds with respect to semi-symmetric non-metric connection in which concircular curvature tensor is ξ −concircularly flat; also φ −concircularly semisymmetric and concircularly pseudo-symmetric.*

Keywords - *Semi-symmetric non-metric connection, Concircular curvature tensor, N (k)-contact metric manifold, Einstein manifold.*

1. Introduction

The concircular curvature tensor is an important (1, 3) type curvature tensor from the Riemannian point of view. Let us consider M *t o* be a $(2n+1)$-dimensional Riemannian manifold. The transformation for every geodesic circle of M into a geodesic circle is called a concircular transformation [1], [2]. In [2], W. Kuhnel found that a concircular transformation is always a conformal transformation**.** In 1940, K. Yano [1] introduced the concircular curvature tensor $\overline{\boldsymbol{Z}}$defined by: [1]

$$\overline{Z}(X,Y)W = R(X,Y)W - \frac{r}{2n(2n+1)}[g(Y,W)X - g(X,W)Y] \tag{1}$$

For $X, Y, W \in T(M)$, and r is the scalar curvature. Riemannian manifolds with vanishing concircular curvature tensor are of constant curvature. We define $\overline{Z}$, the concircular curvature tensor with respect to a semi-symmetric non-metric connection.

$$\overline{Z}(X,Y)W = \overline{R}(X,Y)W - \frac{\overline{r}}{2n(2n+1)}[g(Y,W)X - g(X,W)Y] \tag{2}$$

In [3], A. Barman studied $N(k)$-contact metric manifolds admitting a type of semi-Symmetric non-metric connection. Let M be an $(2n+1)$-dimensional Riemannian manifold with Levi-Civita connection ∇. The semi-symmetric non-metric connection $\overline{\nabla}$ is given by [3]

$$\overline{\nabla}_X Y = \nabla_X Y + \eta(Y)X \tag{3}$$

The torsion tensor T with respect to $\overline{\nabla}$ is given by:

$$T(X,Y) = \overline{\nabla}_X Y - \overline{\nabla}_Y X - [X,Y] = \eta(Y)X - \eta(X)Y \tag{4}$$

Thus, equation (4) defines a semi-symmetric connection.

Using (3), it follows

$$(\overline{\nabla}_{Ug})(X,Y) = -\eta(X)g(Y,U) - \eta(Y)g(X,Y) \neq 0 \tag{5}$$

The connection $\overline{\nabla}$ satisfying (4) and (5) is a type of semi-symmetric non-metric connection. The curvature tensors $\overline{R}$ and R are related by [3]:

$$\overline{R}(X,Y)Z = R(X,Y)Z + g(X,\varphi Z)Y + g(hX,\varphi Z)Y - \eta(X)\eta(Z)Y - g(Y,\varphi Z)X - g(hY,\varphi Z)X + \eta(Y)\eta(Z)X$$

In the present paper, it will be organized as follows: In Section 2, some preliminary results and the definitions that will be needed further are presented. In Section 3, study of the concircular curvature tensor on $N(k)$-contact manifolds with respect to a semi-symmetric non-metric connection which is ξ-concircularly flat. Section 4 is devoted to the study of φ-concircularly $N(k)$-contact manifolds with respect to a semi-symmetric non-metric connection.

In Section 5, studied concircularly pseudo symmetric $N(k)$-contact manifolds with respect to a semi-symmetric non-metric connection and obtained that the manifold is ξ concircular.

2. Preliminaries

A $(2n+1)$-dimensional smooth manifold M is said to be a contact manifold if it admits a global differentiable 1-form η which satisfies the condition.

$$\eta \wedge (d\eta)^{\eta} \neq 0$$

Everywhere on M. Also, a contact manifold admits an almost contact structure (ϕ, ξ, η), where ϕ is a $(1, 1)$ tensor field, ξ is a characteristic vector field, and η is a global 1-form such that

$$\varphi^2 = -1 + \eta \otimes \xi,\ \eta(\xi) = 1,\ \varphi\xi = 0,\ \eta o \varphi = 0 \tag{6}$$

An almost contact structure is said to be normal if the induced almost contact structure J on the product manifold $M \times \mathrm{R}$ is defined by

$$J(X, \lambda \frac{d}{dt}) = (\varphi X - \lambda\xi, \eta \otimes \frac{d}{dt})$$

is integrable, where X is tangent to M, t is the coordinate on R, and λ is a smooth function on $M \times R$. The condition that the almost contact metric structure is normal is equivalent to the vanishing of the torsion tensor

$$[\varphi + \varphi] + 2d\eta \otimes \xi,$$

where $[\phi, \phi]$ is the Nijenhuis tensor of ϕ.

Let g be the compatible Riemannian metric with the almost contact structure (ϕ, ξ, η), that is,

$$g(\varphi X, \varphi Y) = g(X, Y) - \eta(X)\eta(Y),\ g(X, \xi) = \eta(X), g(X, \varphi Y) = -g(\varphi X, Y) \tag{7}$$

for all vector fields $X, Y \in T(M)$. A manifold M together with this almost contact metric structure is called an almost contact metric manifold and denoted by $M(\phi, \xi, \eta, g)$. An almost contact metric structure reduces to a contact metric structure

$$g(X, \varphi Y) = d\eta(X, Y).$$

Moreover, if ∇ denotes the Riemannian connection of g, then the following relation holds:

$$\nabla_X \xi = -\varphi X - \varphi h X, \tag{8}$$

Where h is a (1, 1)-tensor field associated with the structure.

Now, we discuss the notion of an $N(k)$-contact metric manifold. Tanno [4] introduced the k-nullity distribution on a contact metric manifold. The k-nullity distribution $N(k)$ of a Riemannian manifold is defined by

$$N(k): p \to N_p(k) = \{U \in T_p(M) | R(X, Y)U = k(g(Y, U)X - g(X, U)Y)\} \tag{9}$$

for any $X, Y, U \in T(M)$ and constant k, where R denotes the Riemannian curvature tensor and $T(M)$ is the tangent space of M^{2n+1} at any point $p \in M$. If the characteristic vector field ξ of a contact metric manifold belongs to the k-nullity distribution, then the relation

$$R(X,Y)\xi = k[\eta(Y)X - \eta(X)Y] \tag{10}$$

holds. A contact metric manifold with $\xi \in N(k)$ is called an $N(k)$-contact metric manifold. If (11) holds on an $N(k)$-contact metric manifold, it becomes a contact metric manifold. From (10) and (11), it follows that an $N(k)$-contact metric manifold is a Sasakian manifold if and only if $k = 1$. There are many authors who have studied $N(k)$-contact metric manifolds. P. Majhi and UC De [6] studied $N(k)$-contact metric manifolds satisfying certain curvature conditions on the projective curvature tensor. $N(k)$-contact metric manifolds have also been studied by other authors such as Izgurand Sular [6], Ghosh, De, and Taleshian [7], Blair, Konfogiorgos, and Papantoniou [8], Blair [9],[10], and De and Gazi [11]. In an $N(k)$-contact metric manifold, the following relations hold [8][9]:

$$(\nabla_{X\varphi})Y = g(X + hX, Y)\xi - \eta(Y)(X + hX), \tag{11}$$

$$(\nabla_{X\eta})(Y) = g(X + hX, \varphi Y), \tag{12}$$

$$R(\xi, X)Y = k[g(X,Y)\xi - \eta(Y)X], \tag{13}$$

$$R(X,Y)\xi = k[\eta(Y)X - \eta(X)Y], \tag{14}$$

$$r = 2n(2n - 2 + k), \tag{15}$$

$$S(X,Y) = 2(n-1)g(X,Y) + 2(n-1)g(hX,Y) + [2nk - 2(n-1)]\eta(X)\eta(Y); n \geq 1, \tag{16}$$

$$S(\varphi X, \varphi Y) = S(X,Y) - 2nk\eta(X)\eta(Y) - 4(n-1)g(hX,Y), \tag{17}$$

$$S(Y,\xi) = 2nk\eta(Y), \tag{18}$$

$$R(X,Y)Z = k[g(Y,Z)\eta(X) - g(X,Z)\eta(Y)], \tag{19}$$

$$(\nabla_x h)Y = [(1-k)g(X,\varphi Y) + g(X, h\varphi Y)]\xi + \eta(Y)[h(\varphi X + \varphi hX)]. \tag{20}$$

Here, R and S are the curvature tensor and Ricci tensor, respectively, with respect to the Levi-Civita connection. The idea of a semi-symmetric connection on a Riemannian manifold (M, g) was studied by Hayden [12] in 1932. If $\tilde{\nabla} g = 0$then the semi-symmetric connection is said to be a semi-symmetric metric connection. After a long gap, Prvanovic [13] initiated the study of a semi-symmetric connection $\tilde{\nabla}$ satisfying

$$\tilde{\nabla} g \neq 0, \tag{21}$$

with the name pseudo metric semi-symmetric connection, and was followed by Andonie[14]. If (22) holds, a semi-symmetric connection $\tilde{\nabla}$ becomes a semi-symmetric non-metric connection. Agashe and Chafle [15] in 1992 studied a semi-symmetric non-metric connection$\overline{\nabla}$, whose torsion tensor $\overline{T}$satisfies. They proved that the projective curvature tensor of the manifold with respect to these connections is equal to each other. Further, semi-symmetric non-metric connections have been developed by several other authors, such as Liang [16], De and Kamilya [17], Barman [18],[19], Barman and De [20], De and Biswas [21], and many others. A. Barman [3] studied $N(k)$-contact metric manifolds admitting a type of semi-symmetric non-metric connection and gave the following proposition:

Proposition (2.1) For an $N(k)$-contact metric manifold M with respect to the semi-symmetric non-metric connection, $\overline{\nabla}$the curvature tensor $\overline{R}$ is given by

$$\overline{R}(X,Y)Z = R(X,Y)Z + g(X,\varphi Z)Y + g(hX,\varphi Z)Y - \eta(X)\eta(Z)Y - g(Y,\varphi Z)X - g(hY,\varphi Z)X + \eta(Y)\eta(Z)X \tag{22}$$

The Ricci tensor $\overline{S}$ is given by

$$\overline{S}(Y,Z) = S(Y,Z) - 2\eta g(Y,\varphi Z) - 2\eta g(hY,\varphi Z) + 2\eta\eta(Y)\eta(Z), \tag{23}$$

$$\overline{R}(\xi,Y)Z = kg(Y,Z)\xi - (k+1)\eta(Z)Y - g(Y,\varphi Z)\xi - g(hY,\varphi Z)\xi + \eta(Y)\eta(Z)\xi, \tag{24}$$

With the symmetry property

$$\overline{R}(X,Y)Z = \overline{R}(Y,X)Z, \tag{25}$$

The scalar curvature $\overline{r}$ is given by

$$\overline{r} = r + 2n, \tag{26}$$

The Ricci tensor $\overline{S}$ is symmetric and satisfies

$$\overline{S}(Y,\xi) = 2n(k+1)\eta(Y) = \overline{S}(\xi,Y), \tag{27}$$

$$(\overline{\nabla}_{U\eta})(X) = g(U,\varphi X) + g(hU,\varphi X) - \eta(X)\eta(U). \tag{28}$$

3. Concircular Curvature Tensor on N(k)-Contact Metric Manifolds with Respect to Semi-Symmetric Non-Metric Connection

Definition [3.1] The generalized concircular curvature tensor on an N (k)-contact metric manifold with respect to a semi-symmetric non-metric connection is defined

$$\overline{Z}(X,Y)W = \overline{R}(X,Y)W - \frac{\overline{r}}{2n(2n+1)}[g(Y,W)X - g(X,W)Y]. \tag{29}$$

Like the definition of a ξ-conformally flat contact metric manifold [22], we define a ξ-concircularly flat N (k)-contact metric manifold

Definition [3.2] An N (k)-contact metric manifold M with respect to a semi-symmetric non-metric connection is called ξ-concircularly flat if $Z(X,Y)\xi = 0$ holds on M. Put $W = \xi$ in, and using equations (7) and (23), we obtain

$$\left[\frac{2(nk+1)}{2n+1}\right][\eta(Y)X - \eta(X)Y] = 0 \tag{30}$$

Now, $[\eta(Y)X - \eta(X)Y] \neq 0$in a contact metric manifold, in general. Therefore, from (30),

$$k = -\frac{1}{n}. \tag{31}$$

Since $k = -1$ leads to $n = 1$, and M^{2n+1} must be non-Sasakian. Thus, we can state the following theorem:

Theorem[3.1] If a non-Sasakian N(k)-contact metric manifold M with respect to a semi-symmetric non-metric connection is ξ-concircularly flat, then $k = -\frac{1}{n}$ and $\overline{r} = 2n(2n+1)(k+1)$.

Since, M-concircularly flat N (k)-contact metric manifold is always ξ-M-concircularly flat.

We have the following corollary:

Corollary[3.1] In a M-conicularly flat non-saskian N(k)-contact metric manifold M with respect to a semi–symmetric non-metric connection, we have $k = -\frac{1}{n}$ and $\overline{r} = 2n(2n+1)(k+1)$.

4. ϕ-Concircularly Semi-symmetric N(k)-Contact Metric Manifolds With Respect To Non-Metric Connection

Definition [4.1] A N (k)-contact metric manifold is said to be ϕ-concircularly semi-symmetric if$(\overline{Z}(X,Y).\varphi)W = 0$, for all smooth vector fields X, Y, W. In this section, we deal with φ-concircularly semi-symmetric $N(k)$-contact metric manifolds. Suppose

$$(\overline{Z}(X,Y).\phi)W = 0,$$

Then,

$$\overline{Z}(X,Y)\phi W - \phi(\overline{Z}(X,Y)W) = 0. \quad (32)$$

Putting $Y = W = \xi$ in the above equation and using (6) and (22) yields

$$\left[1 - \frac{\overline{r}}{2n(2n+1)}\right](\phi X) = 0 \quad (33)$$

Taking the inner product with Y in (33) yields

$$\left[1 - \frac{\overline{r}}{2n(2n+1)}\right] g(\phi X, Y) = 0.$$

Since $g(\phi X, Y) \neq 0$. It is a non-Sasakian $N(k)$-contact metric manifold. Therefore, we have

$$\overline{r} = 2n(2n+1) \quad (34)$$

Using (26) in (34), we get $r = 4n^2$

Hence, we can state the following theorem

Theorem 4.1. If a $(2n+1)$ dimensional $(n > 1)$ $N(k)$-contact metric manifold M is ϕconcircularly semi-symmetric, then the scalar curvature is $r = 4n^2$.

5. Concircularly Pseudo-symmetric N (k)-Contact Manifolds With Respect To Semi-symmetric Non-metric Connection

A Riemannian manifold is said to be pseudo-symmetric [23] if at every point of the manifold the following relation holds:

$$(R(X,Y).R)(U,V)W = L_R((X \wedge Y).R)(U,V)W$$

for any vector fields $X, Y, U, V, W \in T(M)$, where L_R is a function on M.

The endomorphism $(X \wedge Y)$ is defined by

$$(X \wedge Y)Z = g(Y,Z)X - g(X,Z)Y \quad (35)$$

Now, a Riemannian manifold is said to be concircularly pseudo-symmetric if it satisfies the condition

$$(\overline{R}(X,Y).\overline{Z})(U,V)W = L_Z\big((X \wedge Y).\overline{Z}\big)(U,V)W. \quad (36)$$

where $L_{\overline{Z}}$is a function on M. where $L_{\overline{Z}}f \neq (k+1)$ is a function on M. Let us suppose that an $N(k)$-contact metric manifold with respect to a semi-symmetric non-metric connection satisfies the condition

$$(\overline{R}(X,Y).\overline{Z})(U,V)W = L_{\overline{Z}}\big((X \wedge Y).\overline{Z}\big)(U,V)W. \quad (37)$$

Putting $Y = W = \xi$ in (37), we have

$$\big(\overline{R}(X,\xi).\overline{Z}\big)(U,V)\xi = L_{\overline{Z}}\big((X \wedge \xi).\overline{Z}\big)(U,V)\xi \quad (38)$$

Now, the right-hand side of (38) is given by

$$L_{\overline{Z}}\big((X \wedge \xi).\overline{Z}\big)(U,V)\xi = L_{\overline{Z}}\big[(X \wedge \xi)\overline{Z}(U,V)\xi - \overline{Z}((X \wedge \xi)U,V)\xi - \overline{Z}(U,(X \wedge \xi)V)\xi - \overline{Z}(U,V)(X \wedge \xi)\xi\big]. \quad (39)$$

In view of (2), the concircular curvature tensor with respect to the semi-symmetric non-metric connection of an $(2n+1)$-dimensional $N(k)$-contact manifold is

$$\overline{Z}(X,Y)W = \frac{\overline{r}}{2n(2n+1)}[g(Y,W)X - g(X,W)Y],$$

Where $X, Y, Z \in T(M)$.

Using (2), (6), (22), and (36) in (39), we have

$$\overline{Z}\big((X \wedge \xi).\overline{Z}\big)(\xi, V)\xi = -L_{\overline{Z}}\big[\overline{Z}(X,V)\xi + \eta(V)\overline{Z}(\xi,X)\xi - \eta(X)\overline{Z}(\xi,V)\xi.\big] \tag{40}$$

Further, the left-hand side of (38) is given as

$$\big(\overline{R}(X,\xi).\overline{Z}\big)(U,V)\xi = \overline{R}(X,\xi)\overline{Z}(U,V)\xi - \overline{Z}\big(\overline{R}(X,\xi)U,V\big)\xi - \overline{Z}\big(U,\overline{R}(X,\xi)V\big)\xi - \overline{Z}(U,V)\overline{R}(X,\xi)\xi. \tag{41}$$

Using (2), (6), and (22) in (41), we have $\big(\overline{R}(X,\xi).\overline{Z}\big)(\xi,V)\xi = -(k+1)\big[\overline{Z}(X,V)\xi + \eta(V)\overline{Z}(\xi,X)\xi - \eta(X)\overline{Z}(\xi,V)\xi\big]$. (42)

Using (40) and (42) in (38) yields

$$(L_{\overline{Z}} - (k+1))\big[\overline{Z}(X,V)\xi + \eta(V)\overline{Z}(\xi,X)\xi - \eta(X)\overline{Z}(\xi,V)\xi\big] = 0 \tag{43}$$

By assumption$L_{\overline{Z}}f \neq (k+1)$, we get

$$\overline{Z}(X,V)\xi + \eta(V)\overline{Z}(\xi,X)\xi - \eta(X)\overline{Z}(\xi,V)\xi = 0. \tag{44}$$

Hence, we can state the following theorem.

Theorem [5.1] If a $(2n+1)$-dimensional $(n > 1)$ $N(k)$-contact metric manifold M with respect to a semi-symmetric non-metric connection is concircularly pseudo symmetric, then

$$\tilde{Z}(X,V)\xi + \eta(V)\tilde{Z}(\xi,X)\xi - \eta(X)\tilde{Z}(\xi,V)\xi = 0.$$

Using (2), (7), and (10) in (45), we obtain

$$\overline{Z}(X,V)\xi = \frac{2(nk+1)}{2n+1}[\eta(V)X - \eta(X)V]. \tag{45}$$

where$\xi \in N(k)$. the manifold is ξ-concircular.

Hence, we have the following theorem.

Theorem [5.2] If a $(2n+1)$-dimensional $(n > 1)$ $N(k)$-contact metric manifold M with respect to a semi-symmetric non-metric connection is concircularly pseudo symmetric, then the manifold is ξ-concircular.

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