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ON A TYPE OF QUARTER-SYMMETRIC NON-METRIC ϕ-CONNECTION ON A KENMOTSU MANIFOLD

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Abstract. The object of the present paper is to study a quarter-symmetric non-metric ϕ-connection on a Kenmotsu manifold.

1. Introduction

The product of an almost contact manifold M and the real line R carries a natural almost complex structure. However if one takes M to be an almost contact metric manifold and suppose that the product metric G on $M \times R$ is Kaehlerian, then the structure on M is cosymplectic [8] and not Sasakian. On the other hand Oubina [13] pointed out that if the conformally related metric $e^{2t}G$, t being the coordinate on R, is Kaehlerian, then M is Sasakian and conversely.

In [17], S. Tanno classified connected almost contact metric manifolds whose automorphism groups possess the maximum dimension. For such a manifold M, the sectional curvature of plane sections containing ξ is a constant, say c. If $c > o$, M is a homogeneous Sasakian manifold of constant sectional curvature. If $c = 0$, M is the product of a line or a circle with a Kaehler manifold of constant holomorphic sectional curvature. If $c < o$, M is a warped product space $R \times_f C^n$. In 1971, Kenmotsu studied a class of contact Riemannian manifolds satisfying some special conditions [10]. We call it Kenmotsu manifold . Kenmotsu manifolds have been studied by J.B. Jun , U.C. De and G. Pathak [9], C. Özgür and U.C. De [14], U.C. De and G. Pathak [4], A. Yıldiz, U.C. De and B.E. Acet [19] and others.

In 1975, S. Golab [7] defined and studied quarter-symmetric connection in differentiable manifolds with affine connections. A liner connection ∇ on an n-dimensional Riemannian manifold (M^n, g) is called a quarter-symmetric connection [7] if its

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torsion tensor T satisfies

$$T(X, Y) = \eta(Y)\phi X - \eta(X)\phi Y, \tag{1.1}$$

where η is a 1-form and ϕ is a (1,1) tensor field.

In particular, if $\phi X = X$, then the quarter-symmetric connection reduces to the semi-symmetric connection [6]. Thus the notion of the quarter-symmetric connection generalizes the notion of the semi-symmetric connection.

If moreover, a quarter-symmetric connection ∇ satisfies the condition

$$(\nabla_X g)(Y, Z) \neq 0, \tag{1.2}$$

then ∇ is said to be a quarter-symmetric non-metric connection.

The quarter-symmetric non-metric connection is said to be a quarter-symmetric non-metric ϕ-connection if satisfies the condition

$$(\nabla_X \phi)(Y) = 0, \tag{1.3}$$

for all $X, Y, Z \in \chi(M^n)$.

After S. Golab [7] and S.C.Rastogi ([15], [16]) continued the systematic study of quarter-symmetric metric connection by R.S.Mishra and S.N.Pandey [11], K.Yano and T. Imai [18], S. Mukhopadhyay, A. K. Roy and B. Barua [12], U.C.De and S.C. Biswas [3], U.C. De and G. Pathak [4], J.B. Jun, U.C. De and G. Pathak [9], U.C. De, C. $\ddot{O}zg\ddot{u}r$ and S. Sular [5] and others.

A Riemannian manifold is said to be semisymmetric if its curvature tensor K satisfies the condition

$$K(X, Y).K = 0,$$

where $K(X, Y)$ denotes the curvature operator and Ricci-semisymmetric if

$$K(X, Y).\tilde{S} = 0,$$

where $\tilde{S}$ denotes the Ricci tensor of the manifold.

In this paper we study Kenmotsu manifolds with respect to the quarter-symmetric non-metric ϕ-connection. The paper is organized as follows: After introduction in section 2, we give a brief account of the Kenmotsu manifolds. In section 3, we define a quarter-symmetric non-metric ϕ-connection on a Kenmotsu manifold and we establish the relation between the curvature tensors with respect to the quarter-symmetric non-metric ϕ-connection and the Levi-Civita connection. Section 4, deals with $R.R = 0$ in a Kenmotsu manifold with respect to the quarter-symmetric non-metric ϕ-connection. In section 5, we investigate $R.S = 0$ in a Kenmotsu manifold with respect to the quarter-symmetric non-metric ϕ-connection and we prove that the manifold is Ricci-semisymmetric with respect to the Levi-Civita connection. Finally, we study $S.R = 0$ in a Kenmotsu manifold with respect to the quarter-symmetric non-metric ϕ-connection, where R and S denotes the curvature tensor and the Ricci tensor of the Kenmotsu manifold with respect to the quarter-symmetric non-metric ϕ-connection respectively.

2. Kenmotsu Manifolds

Let M be an $(2n+1)$-dimensional almost contact metric manifold with an almost contact metric structure (ϕ, ξ, η, g) consisting of a $(1,1)$ tensor field ϕ, a vector field ξ, a 1-form η and a Riemannian metric g on M satisfying [2]

$$\phi^2(X) = -X + \eta(X)\xi, \;\; g(X, \xi) = \eta(X), \tag{2.1}$$

$$\eta(\xi) = 1, \;\; \phi(\xi) = 0, \;\; \eta(\phi(X)) = 0, \tag{2.2}$$

$$g(\phi X, \phi Y) = g(X, Y) - \eta(X)\eta(Y), \tag{2.3}$$

$$g(X, \phi Y) = -g(\phi X, Y). \tag{2.4}$$

for all vector fields X ,Y on M . If an almost contact metric manifold satisfies

$$(D_X \phi)(Y) = g(\phi X, Y)\xi - \eta(Y)\phi X, \tag{2.5}$$

then M is called a Kenmotsu manifold [10] . From the above relations , it follows that

$$D_X \xi = X - \eta(X)\xi, \tag{2.6}$$

$$(D_X \eta)(Y) = g(X, Y) - \eta(X)\eta(Y). \tag{2.7}$$

Moreover the curvature tensor K and the Ricci tensor $\tilde{S}$ and the Ricci operator $\tilde{Q}$ of the Kenmotsu manifold with respect to the Levi-Civita connection satisfies

$$K(X, Y)\xi = \eta(X)Y - \eta(Y)X, \tag{2.8}$$

$$K(\xi, X)Y = \eta(Y)X - g(X, Y)\xi, \tag{2.9}$$

$$K(X, \xi)Y = g(X, Y)\xi - \eta(Y)X, \tag{2.10}$$

$$\tilde{S}(\phi X, \phi Y) = \tilde{S}(X, Y) + 2n\eta(X)\eta(Y), \tag{2.11}$$

$$\tilde{S}(X, Y) = g(\tilde{Q}X, Y) = -2ng(X, Y). \tag{2.12}$$

$$\tilde{Q}X = -2nX. \tag{2.13}$$

$$\tilde{S}(X, \xi) = -2n\eta(X). \tag{2.14}$$

3. Curvature tensor with respect to the quarter-symmetric non-metric ϕ-connection

Let (M^{2n+1}, g) be a Kenmotsu Manifold with the Levi-Civita connection D. We define a linear connection ∇ on M by

$$\nabla_X Y = D_X Y - \eta(X)\phi Y + g(X,Y)\xi - \eta(Y)X - \eta(X)Y. \tag{3.1}$$

Using (3.1), the torsion tensor T of M with respect to the connection ∇ is given by

$$T(X,Y) = \nabla_X Y - \nabla_Y X - [X,Y] = \eta(Y)\phi X - \eta(X)\phi Y. \tag{3.2}$$

A linear connection satisfying (3.2) is called a quarter-symmetric connection.
Further using (3.1), we have

$$\begin{aligned}(\nabla_X g)(Y,Z) &= Xg(Y,Z) - g(\nabla_X Y, Z)\\ &\quad -g(Y,\nabla_X Z) = 2\eta(X)g(Y,Z) \neq 0.\end{aligned} \tag{3.3}$$

A linear connection ∇ satisfying (3.2) and (3.3) is called a quarter-symmetric non-metric connection.
Again using (3.1), it follows that

$$(\nabla_X \phi)(Y) = \nabla_X \phi Y - \phi(\nabla_X Y) = 0, \tag{3.4}$$

A linear connection ∇ define by (3.1) satisfying (3.2), (3.3) and (3.4) is called a quarter-symmetric non-metric ϕ-connection.

Conversely, we show that a linear connection ∇ defined on M satisfying (3.2), (3.3) and (3.4) is given by (3.1).
Let H be a tensor field of type $(1,2)$ and

$$\nabla_X Y = D_X Y + H(X,Y). \tag{3.5}$$

Then we have

$$T(X,Y) = H(X,Y) - H(Y,X). \tag{3.6}$$

Further using (3.5), it follows that

$$\begin{aligned}(\nabla_X g)(Y,Z) = \nabla_X g(Y,Z) - g(\nabla_X Y, Z) - g(Y,\nabla_X Z) &= -g(H(X,Y),Z)\\ &\quad -g(Y,H(X,Z)).\end{aligned} \tag{3.7}$$

From (3.3) and (3.7), we obtain

$$g(H(X,Y),Z) + g(Y, H(X,Z)) = -2\eta(X)g(Y,Z). \tag{3.8}$$

Also using (3.8) and (3.6), we get

$$g(T(X,Y),Z) + g(T(Z,X),Y) + g(T(Z,Y),X) = 2g(H(X,Y),Z) + 2\eta(X)g(Y,Z) \\ +2\eta(Y)g(X,Z) - 2\eta(Z)g(X,Y). \tag{3.9}$$

Hence,

$$g(H(X,Y),Z) = \frac{1}{2}[g(T(X,Y),Z) + g(T(Z,X),Y) + g(T(Z,Y),X)] - \eta(X)g(Y,Z) \\ -\eta(Y)g(X,Z) + \eta(Z)g(X,Y) \tag{3.10}$$

Let T' be a tensor field of type $(1,2)$ given by

$$g(T'(X,Y),Z) = g(T(Z,X),Y). \tag{3.11}$$

Then

$$T'(X,Y) = g(X,\phi Y)\xi - \eta(X)\phi Y. \tag{3.12}$$

From (3.10) we have by using (3.11) and (3.12)

$$g(H(X,Y),Z) = \frac{1}{2}[g(T(X,Y),Z) + g(T'(X,Y),Y) + g(T'(Y,X),X)] - \eta(X)g(Y,Z) \\ -\eta(Y)g(X,Z) + \eta(Z)g(X,Y) = -\eta(X)g(\phi Y,Z) - \eta(X)g(Y,Z) - \eta(Y)g(X,Z) \\ +\eta(Z)g(X,Y) \tag{3.13}$$

Hence,

$$H(X,Y) = -\eta(X)\phi Y - \eta(X)Y - \eta(Y)X + g(X,Y)\xi. \tag{3.14}$$

From (3.5) and (3.14), it follows that

$$\nabla_X Y = D_X Y - \eta(X)\phi Y + g(X,Y)\xi - \eta(Y)X - \eta(X)Y.$$

Analogous to the definitions of the curvature tensor of M with respect to the Levi-Civita connection D, we define the curvature tensor of M with respect to the quarter-symmetric non-metric ϕ-connection ∇ by

$$R(X,Y)Z = \nabla_X\nabla_Y Z - \nabla_Y\nabla_X Z - \nabla_{[X,Y]}Z, \tag{3.15}$$

where R be the curvature tensor with respect to the quarter-symmetric non-metric ϕ-connection ∇.

From (3.1) and (3.15), we obtain

$$\begin{aligned}
R(X,Y)Z = K(X,Y)Z + \eta(X)(D_Y\phi)(Z) - \eta(Y)(D_X\phi)(Z) \\
+\eta(X)\eta(Z)\phi Y - \eta(Y)\eta(Z)\phi X + \eta(Y)\eta(Z)X \\
-\eta(X)\eta(Z)Y - \eta(Y)g(X,\phi Z)\xi + \eta(X)g(Y,\phi Z)\xi \\
+g(Y,Z)D_X\xi - g(X,Z)D_Y\xi + g(Y,Z)\eta(X)\xi \\
-g(X,Z)\eta(Y)\xi - g(Y,Z)X + g(X,Z)Y \\
-(D_X\eta)(Y)Z + (D_Y\eta)(X)Z + (D_Y\eta)(X) \\
-(D_X\eta)(Y) - (D_X\eta)(Y)\phi Z + (D_Y\eta)(X)\phi Z. \qquad (3.16)
\end{aligned}$$

Using (2.5), (2.6), (2.7) in (3.16), we have

$$\begin{aligned}
R(X,Y)Z = K(X,Y)Z + \eta(Y)\eta(Z)X - \eta(X)\eta(Z)Y + g(Y,Z)X \\
-g(X,Z)Y. \qquad (3.17)
\end{aligned}$$

From (3.17), it follows that the curvature tensor R satisfies

$$R(X,Y)Z + R(Y,Z)X + R(Z,X)Y = 0, \qquad (3.18)$$

and

$$R(X,Y)Z = -R(Y,X)Z, \qquad (3.19)$$

which implies that R satisfies the first Bianchi identity and skew-symmetric with respect to the first two variables with respect to the quarter-symmetric non-metric ϕ-connection ∇.
Taking the inner product of (3.17) with W, it follows that

$$\begin{aligned}
\tilde{R}(X,Y,Z,W) = \tilde{K}(X,Y,Z,W) + \eta(Y)\eta(Z)g(X,W) - \eta(X)\eta(Z)g(Y,W) \\
+g(Y,Z)g(X,W) - g(X,Z)g(Y,W), \quad (3.20)
\end{aligned}$$

where $\tilde{R}(X,Y,Z,W) = g(R(X,Y)Z,W)$ and $\tilde{K}(X,Y,Z,W) = g(K(X,Y)Z,W)$.
From (3.20) yields,

$$\tilde{R}(X,Y,Z,W) = -\tilde{R}(Y,X,Z,W), \qquad (3.21)$$

and

$$\tilde{R}(X,Y,Z,W) = -\tilde{R}(X,Y,W,Z). \qquad (3.22)$$

Contracting (3.20) over X and W, we obtain

$$S(Y,Z) = \tilde{S}(Y,Z) + 2n\eta(Y)\eta(Z) + 2ng(Y,Z), \qquad (3.23)$$

where S be the Ricci tensor with respect to the quarter-symmetric non-metric ϕ-connection ∇.
From (3.23), we have

$$S(Y,Z) = S(Z,Y), \qquad (3.24)$$

And putting $Z = \xi$ in (3.23) and using (2.14), we get

$$S(Y, \xi) = 2n\eta(Y). \tag{3.25}$$

Again contracting (3.23) over Y and Z, it follows that

$$r = \tilde{r} + 2n(2n + 2), \tag{3.26}$$

where r and $\tilde{r}$ are the scalar curvatures with respect to the quarter-symmetric non-metric ϕ-connection ∇ and the Levi-Civita connection D respectively.

From the above discussions we can state as follows:

Theorem 3.1. *For a Kenmotsu manifold M with respect to the quarter-symmetric non-metric ϕ-connection ∇*
(i) The curvature tensor R is given by (3.17),
(ii) The Ricci tensor S is given by (3.23),
(iii) $R(X, Y)Z + R(Y, Z)X + R(Z, X)Y = 0$,
(iv) $R(X, Y)Z = -R(Y, X)Z$,
(v) $\tilde{R}(X, Y, Z, W) + \tilde{R}(Y, X, Z, W) = 0$,
(vi) $\tilde{R}(X, Y, Z, W) + \tilde{R}(X, Y, W, Z) = 0$,
(vii) $S(Y, \xi) = 2n\eta(Y)$,
(viii) $r = \tilde{r} + 2n(2n + 2)$,
(ix) The Ricci tensor S is symmetric.

4. Kenmotsu manifolds with respect to the quarter-symmetric non-metric ϕ-connection ∇ satisfying $R.R = 0$

Definition 4.1. *A Kenmotsu manifold $M^{2n+1}, (n > 1)$ is said to be an Einstein manifold if its Ricci tensor $\tilde{S}$ of the Levi-Civita connection is of the form*

$$\tilde{S}(X, Y) = ag(X, Y), \tag{4.1}$$

where a is a constant on the manifold .

In this section we suppose that the manifold under consideration is semisymmetric with respect to the quarter-symmetric non-metric ϕ-connection M^{2n+1}, that is,

$$(R(X, Y).R)(U, V)W = 0$$

Then we have

$$\begin{aligned}(R(X, Y))R(U, V)W - R(R(X, Y)U, V)W - R(U, R(X, Y)V)W \\ -R(U, V)R(X, Y)W = 0.\end{aligned} \tag{4.2}$$

Putting $X = \xi$ in (4.2), it follows that

$$\begin{aligned}R(\xi, Y)R(U, V)W - R(R(\xi, Y)U, V)W - R(U, R(\xi, Y)V)W \\ -R(U, V)R(\xi, Y)W = 0.\end{aligned} \tag{4.3}$$

Putting $U = \xi$ in (4.3), we obtain

$$R(\xi, Y)R(\xi, V)W - R(R(\xi, Y)\xi, V)W - R(\xi, R(\xi, Y)V)W$$
$$-R(\xi, V)R(\xi, Y)W = 0. \tag{4.4}$$

Using (2.8), (2.9), (2.10), (2.1), (2.2) and (3.17) in (4.4), we have

$$K(Y, V)W = g(Y, W)V - g(V, W)Y. \tag{4.5}$$

From (4.5), it follows that the manifold is a manifold of constant curvature -1, that is, the manifold under consideration is locally isometric to the hyperbolic space $H_n(-1)$.

Conversly if the manifold is a manifold of constant curvature -1, then it is semisymmetric (K.K=0).

Hence we can state the following:

Theorem 4.1. *If a Kenmotsu manifold is semisymmetric with respect to the quarter-symmetric non-metric ϕ-connection, then the manifold is semisymmetric with respect to the Levi-Civita connection.*

5. Kenmotsu manifolds with respect to the quarter-symmetric non-metric ϕ-connection ∇ satisfying $R.S = 0$

In this section we suppose that the manifold under consideration is Ricci-semisymmetric with respect to the quarter-symmetric non-metric ϕ-connection M^{2n+1}, that is,

$$(R(X, Y).S)(U, V) = 0$$

Then we have

$$S(R(X, Y)U, V) + S(U, R(X, Y)V) = 0. \tag{5.1}$$

Putting $X = \xi$ in (5.1), it follows that

$$S(R(\xi, Y)U, V) + S(U, R(\xi, Y)V) = 0. \tag{5.2}$$

Using (2.9), (2.14), (2.1), (2.2) and (3.17) in (5.2), we obtain

$$\eta(U)S(Y, V) + \eta(V)S(Y, U) = -4n\eta(U)\eta(V)\eta(Y). \tag{5.3}$$

Putting $U = \xi$ in (5.3) and using (2.1) and (2.2), we get

$$\tilde{S}(Y, V) = -2ng(Y, V). \tag{5.4}$$

Therefore , $\tilde{S}(Y,V) = ag(Y,V)$,

where $a = -2n$.

This result shows that the manifold is an Einstein manifold.

Conversly if the manifold is an Einstein manifold, then the manifold is Ricci-semisymmetric ($K.\tilde{S} = 0$).

Therefore, we can state the following:

Theorem 5.1. *If a Kenmotsu manifold is Ricci-semisymmetric with respect to the quarter-symmetric non-metric ϕ-connection, then the manifold is Ricci-semisymmetric with respect to the Levi-Civita connection.*

6. Kenmotsu manifolds with respect to the quarter-symmetric non-metric ϕ-connection ∇ satisfying $S.R = 0$

In this section we suppose that the manifold under consideration is satisfied $S.R = 0$ with respect to the quarter-symmetric non-metric ϕ-connection M^{2n+1}, that is,

$$(S(X,Y).R)(U,V)W = 0. \tag{6.1}$$

This implies

$$(X \wedge_S Y)R(U,V)W + R((X \wedge_S Y)U,V)W + R(U,(X \wedge_S Y)V)W + R(U,V)(X \wedge_S Y)W = 0, \tag{6.2}$$

where the endomorphism $X \wedge_S Y$ is defined by

$$(X \wedge_S Y)W = S(Y,W)X - S(X,W)Y. \tag{6.3}$$

Using the above we obtain

$$S(Y,R(U,V)W)X - S(X,R(U,V)W)Y + S(Y,U)R(X,V)W - S(X,U)R(Y,V)W + S(Y,V)R(U,X)W - S(X,V)R(U,Y)W + S(Y,W)R(U,V)X - S(X,W)R(U,V)Y = 0. \tag{6.4}$$

Putting $Y = \xi$ in (6.4) and using (3.17), (3.25) and (3.23), we get

$$2n\eta(R(U,V)W)X - S(X,R(U,V)W)\xi + 2n\eta(U)R(X,V)W - S(X,U)[K(\xi,V)W + \eta(V)\eta(W)\xi - \eta(W)V + g(V,W)\xi - \eta(W)V] + 2n\eta(V)R(U,X)W - S(X,V)[K(U,\xi)W + \eta(W)U - \eta(U)\eta(W)\xi + \eta(W)U - g(U,W)\xi] + 2n\eta(W)R(U,V)X - S(X,W)[K(U,V)\xi + 2\eta(V)U - 2\eta(U)V] = 0. \tag{6.5}$$

Putting $U = \xi$ in (6.5) and using (3.17), (3.25), (2.8), (2.9), (2.10), (2.14)and (3.23), we have

$$\begin{aligned}\eta(W)S(X,V)\xi + 2nK(X,V)W - 2n\eta(X)\eta(W)V \\ +2ng(V,W)X - 2ng(X,W)V \\ -\eta(V)S(X,W)\xi + S(X,W)V = 0.\end{aligned} \tag{6.6}$$

Contracting X in (6.6) and using (2.1), (2.2) and (2.14), we obtain

$$\tilde{S}(V,W) = -2ng(V,W). \tag{6.7}$$

Therefore,

$\tilde{S}(Y,W) = ag(Y,W)$,

where $a = -2n$

This result shows that the manifold is an Einstein manifold.

Hence we can state the following theorem:

Theorem 6.1. *If a Kenmotsu manifold with respect to the quarter-symmetric non-metric ϕ-connection satisfies $S.R = 0$, then the manifold is an Einstein manifold.*

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