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Conformal Curvature Tensor on Para-kenmotsu Manifold

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Abstract The object of this paper is to obtain the characterisation of para-Kenmotsu (briefly P-Kenmotsu) manifold satisfying the conditions $R(\xi,X).C-C(\xi,X).R=0$ and $R(\xi,X).C-C(\xi,X).R=L_c\,Q(g,C)$, where $C(X,Y)$ is the Weyl-conformal curvature tensor, L_c is some function and X ∈ T(M_n). It is shown respectively that the P-Kenmotsu manifold with these conditions is an η-Einstein manifold and the manifold is either conformally flat (or) L_c = -1 holds on the manifold.

Keywords: *Curvature Tensor, Ricci Tensor, Weyl-semisymmetric para-Kenmotsu manifold, Einstein manifold*

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1. Introduction

The notion of an almost para contact Riemannian manifold was introduced by Sato [10], in 1976. After that, Adati and Matsumoto [1] further defined and studied P-Sasakian and SP-Sasakian manifolds which are regarded as a special kind of an almost contact Riemannian manifolds. Before Sato, in 1972, Kenmotsu [9] defined a class of almost contact Riemannian manifold. In 1995, Sinha and Sai Prasad [13] have defined a class of almost para contact metric manifolds namely, para-Kenmotsu (briefly P-Kenmotsu) and special para-Kenmotsu (briefly SP-Kenmotsu) manifolds.

Let (M_n, g) be an n-dimensional, $n\geq 3$, differentiable manifold of class C^∞. Let ∇ be its Levi-Civita connection, R be the Riemannian Christoffel curvature tensor and $C(X,Y)$ be the Weyl conformal curvature tensor is defined by

$$C(X,Y)Z = R(X,Y)Z-\frac{1}{n-2}\begin{bmatrix} g(Y,Z)QX-g(X,Z)QY \\ +S(Y,Z)X-S(X,Z)Y\end{bmatrix} + \frac{r}{(n-1)(n-2)}[g(Y,Z)X-g(X,Z)Y], \quad (1.1)$$

where Q is the Ricci operator, $S(X,Y)$ is the Ricci tensor and r is the scalar curvature of M_n [4]. The Ricci operator Q and the (0,2)-tensor S^2 are defined by

$$g(QX,Y)=S(X,Y) \quad (1.2)$$

and

$$S^2(X,Y)=S(SX,Y). \quad (1.3)$$

A manifold M_n is conformally flat if $C(X,Y)=0$ and $n\geq 4$. If ∇ C = 0 then M_n is called conformally symmetric and hence it is Weyl-semisymmetric [5].

For a (0, k)-tensor field T, $k\geq 1$, on (M_n, g) we define the tensors $R.T$, $C.T$ and Q(g, T) respectively as [8]:

$$\begin{aligned}&(R(X,Y).T)(X_1,X_2,...,X_k)\\ &=-T(R(X,Y)X_1,X_2,...,X_k)\\ &-...-T(X_1,...,X_{k-1},R(X,Y)X_k),\end{aligned} \quad (1.4)$$

$$\begin{aligned}&(C(X,Y).T)(X_1,X_2,...,X_k)\\ &=-T(C(X,Y)X_1,X_2,...,X_k)\\ &-...-T(X_1,...,X_{k-1},C(X,Y)X_k),\end{aligned} \quad (1.5)$$

$$\begin{aligned}&Q(g,T)(X_1,X_2,...,X_k;X,Y)\\ &=-T((X\wedge Y)X_1,X_2,...,X_k)\\ &-...-T(X_1,...,X_{k-1},(X\wedge Y)X_k);\end{aligned} \quad (1.6)$$

where the endomorphism $(X\wedge Y)$ is defined by

$$(X\wedge Y)Z=g(Y,Z)X-g(X,Z)Y. \quad (1.7)$$

If the tensors $R.C$ and $Q(g,C)$ are linearly dependent then the manifold is called Weyl-pseudosymmetric [8], and it is same as

$$R.C=L_C\,Q(g,C), \quad (1.8)$$

which holds on the set U_C = {x∈ M: C $\neq 0$ at x}, where L_C is some function of U_C. If $R.C=0$, then the manifold is called Weyl-semisymmetric [8].

Locally symmetric, semisymmetric and Pseudosymmetric Para-Sasakian manifolds are widely studied by many geometers [2,6,7]. By studying Weyl-semisymmetric para-Kenmotsu manifolds, Satyanarayana and Sai Prasad have shown that such a manifold is conformally flat and hence it is an SP-Kenmotsu manifold [12]. Later, they extended their work to find the characterisations of the Weyl-pseudosymmetric para-Kenmotsu manifolds which are regarded as the extended classes of Weyl-semisymmetric para-Kenmotsu manifolds.

Through this study, we could obtain the characterisations of the para-Kenmotsu manifolds with the conditions $R(\xi,X).C-C(\xi,X).R=0$ and $R(\xi,X).C-C(\xi,X).R = L_c\,Q(g,C)$.

2. Para-Kenmotsu Manifold

Let M_n be an n-dimensional differentiable manifold equipped with structure tensors (Φ,ξ,η), where Φ is a tensor of type (1, 1), ξ is a vector field, η is a 1-form such that

$$\eta(\xi)=1 \tag{2.1}$$

$$\Phi^2(X)=X-\eta(X)\xi;\ \overline{X}=\Phi X. \tag{2.2}$$

Then M_n is called an almost para contact manifold.

Let g be the Riemannian metric satisfying such that, for all vector fields X and Y on M_n,

$$g(X,\xi)=\eta(X) \tag{2.3}$$

$$\Phi\xi=0,\ \eta(\Phi X)=0,\ \text{rank}\ \Phi=n-1 \tag{2.4}$$

$$g(\Phi X,\Phi Y)=g(X,Y)-\eta(X)\eta(Y). \tag{2.5}$$

Then the manifold M_n [10] is said to admit an almost para contact Riemannian structure (Φ,ξ,η,g).

A manifold M_n of dimension n with Riemannian metric g admitting a tensor field Φ of type (1, 1), a vector field ξ and a 1-form η satisfying (2.1), (2.3) along with

$$(\nabla_X\eta)Y-(\nabla_Y\eta)X=0 \tag{2.6}$$

$$\begin{aligned}(\nabla_X\nabla_Y\eta)Z&=[-g(X,Z)+\eta(X)\eta(Z)]\eta(Y)\\&\quad+[-g(X,Y)+\eta(X)\eta(Y)]\eta(Z)\end{aligned} \tag{2.7}$$

$$\nabla_X\xi=\Phi^2X=X-\eta(X)\xi \tag{2.8}$$

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

is called a para-Kenmotsu manifold or briefly P-Kenmotsu manifold [13], where ∇ is the covariant differentiation with respect to the metric g.

Let (M_n,g) be an n-dimensional Riemannian manifold admitting a tensor field Φ of type (1, 1), a vector field ξ and a 1-form η satisfying

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

$$g(X,\xi)=\eta(X)\ \text{and}\ (\nabla_X\eta)Y=\phi(\overline{X},Y),\ \text{where}\ \phi\ \text{is an associate of}\ \Phi. \tag{2.11}$$

Then M_n is called special para-Kenmotsu manifold or in brief SP-Kenmotsu manifold [13].

It is known that, in a P-Kenmotsu manifold the following relations hold good [13]:

$$S(X,\xi)=-(n-1)\eta(X),\ where\ g(QX,Y)=S(X,Y) \tag{2.12}$$

$$\begin{aligned}g[R(X,Y)Z,\xi]&=\eta[R(X,Y,Z)]\\&=g(X,Z)\eta(Y)-g(Y,Z)\eta(X)\end{aligned} \tag{2.13}$$

$$R(X,\xi)=-1 \tag{2.14}$$

$$R(\xi,X)\xi=X-\eta(X)\xi \tag{2.15}$$

$$R(X,\xi,X)=\xi \tag{2.16}$$

$$R(X,Y,\xi)=\eta(X)Y-\eta(Y)X;\ \text{when}\ X\ \text{is orthogonal to}\ \xi \tag{2.17}$$

$$R(\xi,X)Y=\eta(Y)X-g(X,Y)\xi; \tag{2.18}$$

where Q is the Ricci operator.

An almost para-contact Riemannian manifold M_n is said to be an η-Einstein manifold [11] if the Ricci curvature tensor S is of the form

$$S=aI_d+b\eta\otimes\xi, \tag{2.19}$$

where a and b are smooth functions on M_n. In particular, if $b=0$ then it is said to be an Einstein manifold [11].

Moreover, it is also known that if a P-Kenmotsu manifold is projectively flat then it is an Einstein manifold and its scalar curvature has a negative constant value $-n(n-1)$. Especially, if a P-Kenmotsu manifold is of constant curvature, then scalar curvature has a negative constant value $-n(n-1)$ [13] and in this case

$$S(Y,Z)=-(n-1)g(Y,Z); \tag{2.20}$$

$$S(\Phi Y,\Phi Z)=S(Y,Z)+(n-1)\eta(Y)\eta(Z)\ and \tag{2.21}$$

$$'R(X,Y,Z,W)=\frac{1}{(n-1)}[S(Y,Z)g(X,W)-S(X,Z)g(Y,W)]. \tag{2.22}$$

3. Main Results

Through this study, we could obtain the characterisations of para-Kenmotsu manifolds with the conditions $R(\xi,X).C-C(\xi,X).R=0$ and $R(\xi,X).C-C(\xi,X).R = L_c\,Q(g,C)$.

The tensors $R(\xi,X).C$ and $C(\xi,X).R$ on (M_n, g) are defined by:

$$\begin{aligned}&(R(\xi,X)\cdot C)(Y,Z)W\\&=R(\xi,X)C(Y,Z)W-C(R(\xi,X)Y,Z)W\\&-C(Y,R(\xi,X)Z)W-C(Y,Z)R(\xi,X)W,\end{aligned} \tag{3.1}$$

and

$$\begin{aligned}&(C(\xi,X)\cdot R)(Y,Z)W\\&=C(\xi,X)R(Y,Z)W-R(C(\xi,X)Y,Z)W\\&-R(Y,C(\xi,X)Z)W-R(Y,Z)C(\xi,X)W.\end{aligned}\quad(3.2)$$

Let M_n ($n>3$) be a para-Kenmotsu manifold. Then from (3.1), (3.2) and (1.1), we have

$$\begin{aligned}&(R(\xi,X)\cdot C)(Y,Z)W\\&=R(\xi,X)R(Y,Z)W-R(R(\xi,X)Y,Z)W\\&-R(Y,R(\xi,X)Z)W-R(Y,Z)R(\xi,X)W\\&-\frac{1}{(n-2)}[S(R(\xi,X)Y,W)Z+g(R(\xi,X)Y,W)QZ\\&-S(R(\xi,X)Z,W)Y-g(R(\xi,X)Z,W)QY\\&-S(Z,R(\xi,X)W)Y-g(Z,R(\xi,X)W)QY\\&+S(Y,R(\xi,X)W)Z+g(Y,R(\xi,X)W)QZ]\\&+\frac{r}{(n-1)(n-2)}[g(R(\xi,X)Y,W)Z-g(R(\xi,X)Z,W)Y\\&+g(Y,R(\xi,X)W)Z-g(Z,R(\xi,X)W)Y],\end{aligned}\quad(3.3)$$

and

$$\begin{aligned}&(C(\xi,X)\cdot R)(Y,Z)W\\&=C(\xi,X)R(Y,Z)W-R(C(\xi,X)Y,Z)W\\&-R(Y,C(\xi,X)Z)W-R(Y,Z)C(\xi,X)W\\&-\frac{1}{(n-2)}[S(X,R(Y,Z)W)\xi-S(\xi,R(Y,Z)W)X\\&+(1-n)g(X,R(Y,Z)W)\xi-\eta(R(Y,Z)W)QX\\&-S(X,Y)R(\xi,Z)W+(1-n)\eta(Y)R(X,Z)W\\&-(1-n)g(X,Y)R(\xi,Z)W+\eta(Y)R(QX,Z)W\\&+S(X,Z)R(\xi,Y)W+(1-n)\eta(Z)R(Y,X)W\\&+(1-n)g(X,Z)R(\xi,Y)W+\eta(Z)R(Y,QX)W\\&-S(X,W)R(Y,Z)\xi+(1-n)\eta(W)R(Y,Z)X\\&-(1-n)g(X,W)R(Y,Z)\xi+\eta(W)R(Y,Z)QX]\\&+\frac{r}{(n-1)(n-2)}[g(X,R(Y,Z)W)\xi-g(\xi,R(Y,Z)W)X\\&-g(X,Y)R(\xi,Z)W+\eta(Y)R(X,Z)W\\&+g(X,Z)R(\xi,Y)W+\eta(Z)R(Y,X)W\\&-g(X,W)R(Y,Z)\xi+\eta(W)R(Y,Z)X].\end{aligned}\quad(3.4)$$

By multiplying (3.3) and (3.4) with ξ and on using the condition $(R(\xi,X)\cdot C)-(C(\xi,X)\cdot R)=0$, we get

$$\begin{aligned}&\frac{1}{(n-2)}[S(R(\xi,X)Y,W)\eta(Z)\\&+(1-n)g(R(\xi,X)Y,W)\eta(Z)\\&-S(R(\xi,X)Z,W)\eta(Y)\\&-(1-n)g(R(\xi,X)Z,W)\eta(Y)\\&-S(Z,R(\xi,X)W)\eta(Y)+S(Y,R(\xi,X)W)\eta(Z)\\&-(1-n)g(Z,R(\xi,X)W)\eta(Y)\\&+(1-n)g(Y,R(\xi,X)W)\eta(Z)\\&-S(X,R(Y,Z)W)-(1-n)g(X,R(Y,Z)W)\\&+S(X,Y)g(Z,W)-(1-n)g(X,Y)g(Z,W)\\&+S(X,Z)g(Y,W)+(1-n)g(X,Z)g(Y,W)]\\&-\frac{r}{(n-1)(n-2)}[g(R(\xi,X)Y,W)\eta(Z)\\&-g(R(\xi,X)Z,W)\eta(Y)-g(X,Y)g(Z,W)\\&+g(Y,R(\xi,X)W)\eta(Z)-g(Z,R(\xi,X)W)\eta(Y)\\&-g(X,R(Y,Z)W+g(X,Z)g(Y,W)]=0.\end{aligned}\quad(3.5)$$

By putting $Y=W=\xi$ in (3.5) and on using (2.12) and (2.13), we get

$$\begin{aligned}&\frac{1}{(n-2)}[5(1-n)g(X,Z)-8(1-n)\eta(X)\eta(Z)\\&+3S(X,Z)-\frac{4r}{(n-1)(n-2)}[g(X,Z)-\eta(X)\eta(Z)]=0,\end{aligned}\quad(3.6)$$

which on simplification gives

$$\begin{aligned}S(X,Z)=&[\frac{4r}{3(n-1)}-\frac{5(1-n)}{3}]g(X,Z)\\&+[\frac{8(1-n)}{3}-\frac{4r}{3(n-1)}]\eta(X)\eta(Z).\end{aligned}\quad(3.7)$$

This shows that the manifold is an η -Einstein manifold.Thus, we state the following theorem.

Theorem 3.1: A P-Kenmotsu manifold M_n ($n>3$) with the condition $R(\xi,X).C-C(\xi,X).R=0$ is an η-Einstein manifold.

Further, let us consider para-Kenmotsu manifold M_n ($n>3$) with the condition $R(\xi,X).C-C(\xi,X).R$ $=L_c\,Q(g,C)$.

Then, we have

$$\begin{aligned}&R(\xi,X)C(Y,Z)W-C(R(\xi,X)Y,Z)W\\&-C(Y,R(\xi,X)Z)W-C(Y,Z)R(\xi,X)W\\&-C(\xi,X)R(Y,Z)W+R(C(\xi,X)Y,Z)W\\&+R(Y,C(\xi,X)Z)W+R(Y,Z)C(\xi,X)W\\&=L_c[(\xi\wedge X)C(Y,Z)W-C((\xi\wedge X)Y,Z)W\\&-C(Y,(\xi\wedge X)Z)W-C(Y,Z)(\xi\wedge X)W].\end{aligned}\quad(3.8)$$

By multiplying (3.8) with ξ and on using (1.7), we get

$$\begin{aligned}&\eta(R(\xi,X)C(Y,Z)W)-\eta(C(R(\xi,X)Y,Z)W)\\&-\eta(C(Y,R(\xi,X)Z)W)-\eta(C(Y,Z)R(\xi,X)W)\\&-\eta(C(\xi,X)R(Y,Z)W)+\eta(R(C(\xi,X)Y,Z)W)\\&+\eta(R(Y,C(\xi,X)Z)W)+\eta(R(Y,Z)C(\xi,X)W)\\&=L_c[g(X,C(Y,Z)W)-\eta(C(Y,Z)W)\eta(X)\\&-g(X,Y)\eta(C(\xi,Z)W)+\eta(C(X,Z)W)\eta(Y)\\&-g(X,Z)\eta(C(Y,\xi)W)+\eta(C(Y,X)W)\eta(Z)\\&+\eta(C(Y,Z)X)\eta(W)].\end{aligned}\quad(3.9)$$

By using the equations (2.12) and (2.13), the above equation reduces to

$$\begin{aligned}&\eta(C(Y,Z)W)\eta(X)-g(X,C(Y,Z)W)\\&-\eta(C(R(\xi,X)Y,Z)W)-\eta(C(Y,R(\xi,X)Z)W)\\&-\eta(C(Y,Z)R(\xi,X)W)-\eta(C(\xi,X)R(Y,Z)W)\\&+g(C(\xi,X)Y,W)\eta(Z)-g(Z,W)\eta(C(\xi,X)Y)\\&+g(Y,W)\eta(C(\xi,X)Z)-g(C(\xi,X)Z,W)\eta(Y)\end{aligned}$$

$$+g(Y,C(\xi,X)W)\eta(Z)-g(Z,C(\xi,X)W)\eta(Y)$$
$$=L_c[g(X,C(Y,Z)W)-\eta(C(Y,Z)W)\eta(X)$$
$$-g(X,Y)\eta(C(\xi,Z)W)+\eta(C(X,Z)W)\eta(Y) \quad (3.10)$$
$$-g(X,Z)\eta(C(Y,\xi)W)+\eta(C(Y,X)W)\eta(Z)$$
$$+\eta(C(Y,Z)X)\eta(W)].$$

By interchanging X and Y in (3.10) and on subtracting it from (3.10), we get

$$\eta(C(Y,Z)W)\eta(X)-\eta(C(X,Z)W)\eta(Y)$$
$$-g(X,C(Y,Z)W)+g(Y,C(X,Z)W)$$
$$+\eta(C(R(X,Y)\xi,Z)W)-\eta(C(Y,R(\xi,X)Z)W)$$
$$+\eta(C(X,R(\xi,Y)Z)W)-\eta(R(\xi,X)C(Y,Z)W)$$
$$+\eta(R(\xi,Y)C(X,Z)W)-\eta(C(\xi,X)R(Y,Z)W)$$
$$+\eta(C(\xi,Y)R(X,Z)W)+g(Y,W)\eta(C(\xi,X)Z) \quad (3.11)$$
$$-g(X,W)\eta(C(\xi,Y)Z)$$
$$=L_c[g(X,C(Y,Z)W)-g(Y,C(X,Z)W)$$
$$+2\eta(C(X,Z)W)\eta(Y)-2\eta(C(Y,Z)W)\eta(X)$$
$$-2\eta(C(X,Y)W)\eta(Z)+g(X,Z)\eta(C(\xi,Y)W)$$
$$-g(Y,Z)\eta(C(\xi,X)W)+\eta(C(Y,X)Z)\eta(W)].$$

By putting $Z=\xi$ in (3.11), we get

$$(1+L_c)[3\eta(C(X,\xi)W)\eta(Y)-3\eta(C(Y,\xi)W)\eta(X)$$
$$+g(X,C(Y,\xi)W)-g(Y,C(X,\xi)W) \quad (3.12)$$
$$-2\eta(C(X,Y)W)]=0.$$

On contracting the above equation with respect to X, we get

$$(1+L_c)[\eta(C(\xi,Y)W)]=0. \quad (3.13)$$

From (3.13), if $L_c=0$, the manifold M_n is Weyl-semisymmetric, and hence we have

$$\eta(C(\xi,Y)W)=0; \quad (3.14)$$

which gives us

$$S(Y,W)=[\frac{r}{(n-1)}+1]g(Y,W)-[\frac{r}{(n-1)}+n]\eta(Y)\eta(W). \quad (3.15)$$

This shows that the manifold M_n is an η-Einstein manifold.

Now, by using the equations (3.14) and (3.15), the equation (3.11) takes the form $C(Y,Z,W,X)=0$, means that the manifold is conformally flat and hence it is an SP-Kenmotsu manifold [12].

If $L_c\neq 0$ and $\eta(C(\xi,Y)W)=0$ in (3.13), we have $L_c=-1$. Thus, we state the following theorem.

Theorem 3.2: A Para-Kenmotsu manifold M_n ($n>3$) with the condition $R(\xi,X).C-C(\xi,X).R=L_c\,Q(g,C)$ is either conformally flat, in which M_n is an SP-Kenmotsu manifold, or $L_c=-1$ holds on M_n.

4. Conclusion

In this paper, we have obtained the curvature properties of para-Kenmotsu manifold with the conditions $R(\xi,X).C-C(\xi,X).R = 0$ and $R(\xi,X).C-C(\xi,X).R = L_c\,Q(g,C)$. Some of these results obtained are in similar to the results reported earlier in the case of para-Sasakian manifolds [3] .

Statement of Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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