Hindawi Publishing Corporation
International Journal of Mathematics and Mathematical Sciences
Volume 2012, Article ID 757032, 9 pages
doi:10.1155/2012/757032

Research Article

On Concircular ϕ-Recurrent K-Contact Manifold Admitting Semisymmetric Metric Connection

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Received 29 March 2012; Accepted 29 May 2012

Academic Editor: J. Dydak

In the present paper, we have studied ϕ-recurrent and concircular ϕ-recurrent K-contact manifold with respect to semisymmetric metric connection and obtained some interesting results.

1. Introduction

The idea of semisymmetric linear connection on a differentiable manifold was introduced by Friedmann and Schouten [1]. In [2], Hayden introduced idea of metric connection with torsion on a Riemannian manifold. Further, some properties of semisymmetric metric connection has been studied by Yano [3]. In [4], Golab defined and studied quarter-symmetric connection on a differentiable manifold with affine connection, which generalizes the idea of semisymmetric connection. Various properties of semisymmetric metric connection and quarter-symmetric metric connection have been studied by many geometers like Sharfuddin and Hussain [5], Amur and Pujar [6], Rastogi [7, 8], Mishra and Pandey [9], Bagewadi et al. [10–14], De et al. [15, 16], and many others.

The notion of local symmetry of a Riemannian manifold has been weakened by many authors in several ways to a different extent. As a weaker version of local symmetry, Takahashi [17] introduced the notion of local ϕ-symmetry on a Sasakian manifold. Generalizing the notion of ϕ-symmetry, De et al. [18] introduced the notion of ϕ-recurrent Sasakian manifolds.

The paper is organized as follows. Section 2 is devoted to preliminaries. In Section 3, we study semisymmetric metric connection in a K-contact manifold. In Section 4, it is proved that a ϕ-recurrent K-contact manifold with respect to semisymmetric metric connection is an

Einstein manifold. Finally, in Section 5 it is also shown that concircular ϕ-recurrent K-contact manifold admitting semisymmetric metric connection is an Einstein manifold, and the characteristic vector field ξ and the vector field ρ associated to the 1-form A are codirectional.

2. Preliminaries

An n-dimensional differentiable manifold M is said to have an almost contact structure (ϕ, ξ, η) if it carries a tensor field ϕ of type $(1,1)$, a vector field ξ, and a 1-form η on M, respectively, such that,

$$\phi^2 = -I + \eta \otimes \xi, \qquad \eta(\xi) = 1, \qquad \eta \circ \phi = 0, \qquad \phi\xi = 0. \tag{2.1}$$

Thus a manifold M equipped with this structure (ϕ, ξ, η) is called an almost contact manifold and is denoted by (M, ϕ, ξ, η). If g is a Riemannian metric on an almost contact manifold M such that,

$$g(\phi X, \phi Y) = g(X, Y) - \eta(X)\eta(Y), \qquad g(X, \xi) = \eta(X), \tag{2.2}$$

where X, Y are vector fields defined on M, then, M is said to have an almost contact metric structure (ϕ, ξ, η, g), and M with this structure is called an almost contact metric manifold and is denoted by (M, ϕ, ξ, η, g).

If on (M, ϕ, ξ, η, g) the exterior derivative of 1-form η satisfies

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

then (ϕ, ξ, η, g) is said to be a contact metric structure, and M equipped with a contact metric structure is called an contact metric manifold.

If moreover ξ is killing vector field on M, then, M is called a K-contact Riemannian manifold [19, 20]. A K-contact Riemannian manifold is called Sasakian [19], if the relation

$$(\nabla_X \phi) Y = g(X, Y)\xi - \eta(Y) X \tag{2.4}$$

holds, where ∇ denotes the operator of covariant differentiation with respect to g.

In a K-contact manifold M, the following relations holds:

$$\nabla_X \xi = -\phi X, \tag{2.5}$$

$$g(R(X, Y)Z, \xi) = g(Y, Z)\eta(X) - g(X, Z)\eta(Y), \tag{2.6}$$

$$S(X, \xi) = (n - 1)\eta(X), \tag{2.7}$$

for all vector fields X, Y, and Z. Here R and S are the Riemannian curvature tensor and the Ricci tensor of M, respectively.

Definition 2.1. A K-contact manifold M is said to be ϕ-recurrent if there exists a nonzero 1-form A such that,

$$\phi^2((\nabla_W R)(X,Y)Z) = A(W)R(X,Y)Z, \tag{2.8}$$

where A is defined by $A(W) = g(W,\rho)$, and ρ is a vector field associated with the 1-form A.

Definition 2.2. A K-contact manifold M is said to be concircular ϕ-recurrent [12] if there exists a non-zero 1-form A such that,

$$\phi^2\left(\left(\nabla_W \overline{C}\right)(X,Y)Z\right) = A(W)\overline{C}(X,Y)Z, \tag{2.9}$$

where $\overline{C}$ is a concircular curvature tensor given by [21] as follows:

$$\overline{C}(X,Y)Z = R(X,Y)Z - \frac{r}{n(n-1)}[g(Y,Z)X - g(X,Z)Y], \tag{2.10}$$

where R is the Riemannian curvature tensor and r is the scalar curvature.

A linear connection $\widetilde{\nabla}$ in an n-dimensional differentiable manifold M is said to be a semisymmetric connection if its torsion tensor T is of the form

$$T(X,Y) = \widetilde{\nabla}_X Y - \widetilde{\nabla}_Y X - [X,Y] = \eta(Y)X - \eta(X)Y, \tag{2.11}$$

for all X, Y on TM. A semisymmetric connection $\widetilde{\nabla}$ is called semisymmetric metric connection, if it further satisfies $\widetilde{\nabla}g = 0$.

3. Semisymmetric Metric Connection in a K-Contact Manifold

A semisymmetric metric connection $\widetilde{\nabla}$ in a K-contact manifold can be defined by

$$\widetilde{\nabla}_X Y = \nabla_X Y + \eta(Y)X - g(X,Y)\xi, \tag{3.1}$$

where ∇ is the Levi-Civita connection on M [3].

A relation between the curvature tensor of M, with respect to the semisymmetric metric connection $\widetilde{\nabla}$ and the Levi-Civita connection, ∇ is given by

$$\begin{aligned}\widetilde{R}(X,Y)Z = R(X,Y)Z &+ [g(\phi Y,Z)X - g(\phi X,Z)Y] + [g(Y,Z)\phi X - g(X,Z)\phi Y] \\ &+ [g(\phi X,\phi Z)Y - g(\phi Y,\phi Z)X] + [\eta(X)g(Y,Z) - \eta(Y)g(X,Z)]\xi,\end{aligned} \tag{3.2}$$

where $\widetilde{R}$ and R are the Riemannian curvatures of the connections $\widetilde{\nabla}$ and ∇, respectively.

From (3.2), it follows that

$$\widetilde{S}(Y,Z) = S(Y,Z) - (n-2)g(Y,Z) + (n-2)g(\phi Y,Z) + (n-2)\eta(Y)\eta(Z), \tag{3.3}$$

where $\widetilde{S}$ and S are the Ricci tensors of the connections $\widetilde{\nabla}$ and ∇, respectively.

Contracting (3.3), we get

$$\tilde{r} = r - (n-1)(n-2), \tag{3.4}$$

where $\tilde{r}$ and r are the scalar curvatures of the connections $\tilde{\nabla}$ and ∇, respectively.

4. ϕ-Recurrent K-Contact Manifold with respect to Semisymmetric Metric Connection

A K-contact manifold is called ϕ-recurrent with respect to the semisymmetric metric connection if its curvature tensor $\tilde{R}$ satisfies the following condition:

$$\phi^2\left(\left(\tilde{\nabla}_W \tilde{R}\right)(X,Y)Z\right) = A(W)\tilde{R}(X,Y)Z. \tag{4.1}$$

By virtue of (2.1) and (4.1), we have

$$-\left(\tilde{\nabla}_W \tilde{R}\right)(X,Y)Z + \eta\left(\left(\tilde{\nabla}_W \tilde{R}\right)(X,Y)Z\right)\xi = A(W)\tilde{R}(X,Y)Z, \tag{4.2}$$

from which, it follows that

$$-g\left(\left(\tilde{\nabla}_W \tilde{R}\right)(X,Y)Z,U\right) + \eta\left(\left(\tilde{\nabla}_W \tilde{R}\right)(X,Y)Z\right)g(\xi,U) = A(W)g\left(\tilde{R}(X,Y)Z,U\right). \tag{4.3}$$

Let $\{e_i\}$, $i = 1,2,\ldots,n$ be an orthonormal basis of the tangent space at any point of the manifold. Then putting $X = U = e_i$ in (4.3) and taking summation over i, $1 \le i \le n$, we get

$$-\left(\tilde{\nabla}_W \tilde{S}\right)(Y,Z) + \sum_{i=1}^{n}\eta\left(\left(\tilde{\nabla}_W \tilde{R}\right)(e_i,Y)Z\right)\eta(e_i) = A(W)\tilde{S}(Y,Z). \tag{4.4}$$

Put $Z = \xi$, then the second term of (4.4) takes the following form:

$$\begin{aligned} g\left(\left(\tilde{\nabla}_W \tilde{R}\right)(e_i,Y)\xi,\xi\right) &= g\left(\tilde{\nabla}_W \tilde{R}(e_i,Y)\xi,\xi\right) - g\left(\tilde{R}\left(\tilde{\nabla}_W e_i,Y\right)\xi,\xi\right) \\ &\quad - g\left(\tilde{R}\left(e_i,\tilde{\nabla}_W Y\right)\xi,\xi\right) - g\left(\tilde{R}(e_i,Y)\tilde{\nabla}_W \xi,\xi\right). \end{aligned} \tag{4.5}$$

On simplification, we obtain $g((\tilde{\nabla}_W \tilde{R})(e_i,Y)\xi,\xi) = 0$.

Now (4.4) implies that

$$\left(\tilde{\nabla}_W \tilde{S}\right)(Y,\xi) = -A(W)\tilde{S}(Y,\xi). \tag{4.6}$$

We know that

$$\left(\tilde{\nabla}_W \tilde{S}\right)(Y,\xi) = \tilde{\nabla}_W \tilde{S}(Y,\xi) - \tilde{S}\left(\tilde{\nabla}_W Y,\xi\right) - \tilde{S}\left(Y,\tilde{\nabla}_W \xi\right). \tag{4.7}$$

Using (3.3), (2.5), and (2.7) in the above relation, we get

$$\begin{aligned}\left(\tilde{\nabla}_W\tilde{S}\right)(Y,\xi) = S(Y,\phi W) - S(Y,W) - (n-1)g(Y,\phi W)\\ + (n-1)g(Y,W) + 2(n-2)g(\phi Y,\phi W).\end{aligned} \tag{4.8}$$

In view of (4.6) and (4.8), we have

$$S(Y,W)-S(Y,\phi W)+(n-1)g(Y,\phi W)-(n-1)g(Y,W)-2(n-2)g(\phi Y,\phi W)=(n-1)A(W)\eta(Y). \tag{4.9}$$

Again putting $Y = \phi Y$ in (4.9), we get

$$S(\phi Y,W) - S(\phi Y,\phi W) + (n-1)g(\phi Y,\phi W) - (n-1)g(\phi Y,W) + 2(n-2)g(Y,\phi W) = 0. \tag{4.10}$$

Interchanging Y and W in (4.10), we obtain

$$S(\phi W,Y) - S(\phi W,\phi Y) + (n-1)g(\phi W,\phi Y) - (n-1)g(\phi W,Y) + 2(n-2)g(W,\phi Y) = 0. \tag{4.11}$$

Adding (4.10) and (4.11) which on simplification, we have

$$S(Y,W) = (n-1)g(Y,W). \tag{4.12}$$

Therefore, we can state the following.

Theorem 4.1. *A ϕ-recurrent K-contact manifold with respect to semisymmetric metric connection is an Einstein manifold.*

5. Concircular ϕ-Recurrent K-Contact Manifold with respect to Semisymmetric Metric Connection

Let us consider a concircular ϕ-recurrent K-contact manifold with respect to the semisymmetric metric connection defined by

$$\phi^2\left(\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z\right) = A(W)\tilde{\tilde{C}}(X,Y)Z, \tag{5.1}$$

where $\tilde{\tilde{C}}$ is a concircular curvature tensor with respect to the semisymmetric metric connection given by

$$\tilde{\tilde{C}}(X,Y)Z = \tilde{R}(X,Y)Z - \frac{\tilde{r}}{n(n-1)}\left[g(Y,Z)X - g(X,Z)Y\right]. \tag{5.2}$$

By virtue of (2.1) and (5.1), we have

$$-\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z+\eta\left(\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z\right)\xi=A(W)\tilde{\tilde{C}}(X,Y)Z, \tag{5.3}$$

from which, it follows that

$$-g\left(\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z,U\right)+\eta\left(\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z\right)g(\xi,U)=A(W)g\left(\tilde{\tilde{C}}(X,Y)Z,U\right), \tag{5.4}$$

where

$$\begin{aligned}\left(\tilde{\nabla}_W\tilde{\tilde{C}}\right)(X,Y)Z= {}&((\nabla_W R)(X,Y)Z)+3[g(Y,W)\eta(Z)X-g(X,W)\eta(Z)Y]\\&+3[g(Y,Z)g(W,X)-g(X,Z)g(W,Y)]\xi\\&+2[\eta(X)g(\phi W,Z)Y-\eta(Y)g(\phi W,Z)X]\\&+2[\eta(Y)g(X,Z)-\eta(X)g(Y,Z)]\phi W+[g(Y,Z)\eta(X)-g(X,Z)\eta(Y)]W\\&+2\eta(W)[\eta(Y)g(X,Z)-\eta(X)g(Y,Z)]\xi\\&+2\eta(Z)\eta(W)[\eta(X)Y-\eta(Y)X]+g(Z,W)[\eta(Y)X-\eta(X)Y]\\&-g(W,R(X,Y)Z)\xi-\eta(X)R(W,Y)Z\\&-\eta(Y)R(X,W)Z-\eta(Z)R(X,Y)W\\&-\frac{\nabla_W r}{n(n-1)}[g(Y,Z)X-g(X,Z)Y].\end{aligned} \tag{5.5}$$

Let $\{e_i\}$, $i=1,2,\ldots,n$ be an orthonormal basis of the tangent space at any point of the manifold. Then putting $X=U=e_i$ in (5.4) and taking summation over i, $1\le i\le n$, we get

$$\left(\tilde{\nabla}_W\tilde{S}\right)(Y,Z)-\frac{\tilde{\nabla}_W\tilde{r}}{n}g(Y,Z)=-\frac{\tilde{\nabla}_W\tilde{r}}{n(n-1)}[g(Y,Z)-\eta(Y)\eta(Z)]-A(W)\left[\tilde{S}(Y,Z)-\frac{\tilde{r}}{n}g(Y,Z)\right]. \tag{5.6}$$

Replacing Z by ξ in (5.6), we obtain

$$\left(\tilde{\nabla}_W\tilde{S}\right)(Y,\xi)=\frac{\tilde{\nabla}_W\tilde{r}}{n}\eta(Y)-A(W)\left[\tilde{S}(Y,\xi)-\frac{\tilde{r}}{n}\eta(Y)\right]. \tag{5.7}$$

We know that

$$\left(\tilde{\nabla}_W\tilde{S}\right)(Y,\xi)=\tilde{\nabla}_W\tilde{S}(Y,\xi)-\tilde{S}\left(\tilde{\nabla}_W Y,\xi\right)-\tilde{S}\left(Y,\tilde{\nabla}_W\xi\right). \tag{5.8}$$

Using (3.3), (2.5) and (2.7), the above relation becomes

$$\left(\tilde{\nabla}_W \tilde{S}\right)(Y,\xi) = S(Y,\phi W) - S(Y,W) - (n-1)g(Y,\phi W) + (n-1)g(Y,W) + 2(n-2)g(\phi Y,\phi W). \tag{5.9}$$

In view of (5.7) and (5.9), we obtain

$$\begin{aligned} S(Y,\phi W) - S(Y,W) - (n-1)g(Y,\phi W) + (n-1)g(Y,W) + 2(n-2)g(Y,W) - 2(n-2)\eta(Y)\eta(W) \\ = \frac{\nabla_W r}{n}\eta(Y) - A(W)\left[\frac{2(n-1)^2 - r}{n}\eta(Y)\right]. \end{aligned} \tag{5.10}$$

Replacing Y by ϕY in (5.10), we have

$$S(\phi Y,\phi W) - S(\phi Y,W) - (n-1)g(\phi Y,\phi W) + (n-1)g(\phi Y,W) + 2(n-2)g(\phi Y,W) = 0. \tag{5.11}$$

Interchanging Y and W in (5.11), we get

$$S(\phi W,\phi Y) - S(\phi W,Y) - (n-1)g(\phi W,\phi Y) + (n-1)g(\phi W,Y) + 2(n-2)g(\phi W,Y) = 0. \tag{5.12}$$

Adding (5.11) and (5.12), which on simplification, we have

$$S(Y,W) = (n-1)g(Y,W). \tag{5.13}$$

Thus, we obtain the following theorem.

Theorem 5.1. *A Concircular ϕ-recurrent K-contact manifold with respect to semisymmetric metric connection is an Einstein manifold.*

Next, from (5.3), one has

$$\left(\tilde{\nabla}_W \tilde{\tilde{C}}\right)(X,Y)Z = \eta\left(\left(\tilde{\nabla}_W \tilde{\tilde{C}}\right)(X,Y)Z\right)\xi - A(W)\tilde{\tilde{C}}(X,Y)Z. \tag{5.14}$$

Now, using (3.2), (3.4), (5.5), and Bianchi's identity in (5.14), one obtains

$$\begin{aligned} A(W)\eta(R(X,Y)Z) + A(X)\eta(R(Y,W)Z) + A(Y)\eta(R(W,X)Z) \\ = -A(W)[g(\phi Y,Z)\eta(X) - g(\phi X,Z)\eta(Y)] \\ - A(X)[g(\phi W,Z)\eta(Y) - g(\phi Y,Z)\eta(W)] \\ - A(Y)[g(\phi X,Z)\eta(W) - g(\phi W,Z)\eta(X)] \end{aligned}$$

$$+\frac{r-(n-1)(n-2)}{n(n-1)}A(W)\left[g(Y,Z)\eta(X)-g(X,Z)\eta(Y)\right]$$
$$+\frac{r-(n-1)(n-2)}{n(n-1)}A(X)\left[g(W,Z)\eta(Y)-g(Y,Z)\eta(W)\right]$$
$$+\frac{r-(n-1)(n-2)}{n(n-1)}A(Y)\left[g(X,Z)\eta(W)-g(W,Z)\eta(X)\right]. \tag{5.15}$$

Putting $Y = Z = e_i$ in (5.15) and taking summation over i, $1 \leq i \leq n$, one gets

$$\left[\frac{-n(n-1)(n-2)+r(n-2)-(n-1)(n-2)^2}{n(n-1)}\right]A(X)\eta(W) + \left[\frac{n(n-1)(n-2)-r(n-2)+(n-1)(n-2)^2}{n(n-1)}\right]A(W)\eta(X) = A(\phi W)\eta(X)-A(\phi X)\eta(W). \tag{5.16}$$

Replacing X by ξ in (5.16), one gets

$$\left[\frac{[r(n-2)+2(n-1)(n-2)]^2+n^2(n-1)^2}{n(n-1)[r(n-2)+2(n-1)(n-2)]}\right]\left[A(W)-A(\xi)\eta(W)\right]=0, \tag{5.17}$$

therefore

$$A(W)=\eta(W)\eta(\rho), \tag{5.18}$$

for any vector field W.

Hence, one states the following.

Theorem 5.2. *In a concircular ϕ-recurrent K-contact manifold admitting semisymmetric metric connection the characteristic vector field ξ and the vector field ρ associated to the 1-form A are co-directional and the 1-form A is given by* (5.18).

Acknowledgment

The authors express their thanks to DST (Department of Science and Technology), Government of India for providing financial assistance under major research project (no. SR/S4/MS:482/07).

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