PUBLICATIONS DE L'INSTITUT MATHÉMATIQUE
Nouvelle série tome 56 (70), 1994, 102–110

ON THE AC-CONTACT BOCHNER CURVATURE TENSOR FIELD ON ALMOST COSYMPLECTIC MANIFOLDS

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Communicated by Mileva Prvanović

Abstract. On an almost cosymplectic manifold we define a new modified contact Bochner curvature tensor field which is invariant with respect to D-homothetic deformation. Then we generalize a theorem of Olszak [**5**] and describe some manifolds with vanishing its new modified contact Bochner curvature tensor field.

1. Introduction. Olszak [**5**, Theorem 6.2] got the necessary and sufficient condition for a conformally flat almost cosymplectic manifold to be cosymplectic. On the other hand, Matsumoto and Chuman [**4**] defined contact Bochner curvature tensor in Sasakian manifolds (see also Yano [**8**]). This tensor is invariant with respect to D-homothetic deformations (see Tanno [**7**] about D-homothetic deformations). In this paper we modify contact Bochner curvature tensor and define a new modified contact Bochner curvature tensor field which is invariant with respect to D-homothetic deformations of an almost cosymplectic manifold. We call it AC-contact Bochner curvature tensor. Then, by using AC-contact Bochner curvature, we get a generalization of an Olszak's theorem [**5**, Theorem 6.2]. Moreover, we consider an almost cosymplectic manifold with constant ϕ-sectional curvature and another one with vanishing AC-contact Bochner curvature.

2. Preliminaries. Let (M,ϕ,ξ,η,g) be a $(2n+1)$-dimensional almost contact Riemannian manifold, that is, let M be a differentiable manifold and (ϕ,ξ,η,g) an almost contact Riemannian structure on M, formed by tensor fields ϕ,ξ,η, of type (1,1), (1,0) and (0,1), respectively, and a Riemannian metric g such that

$$\begin{aligned}\phi^2=-I+\eta\otimes\xi,\quad \phi\xi=0,\quad \eta\cdot\phi=0,\quad \eta(\xi)=1,\\ \eta(X)=g(X,\xi),\quad g(\phi X,\phi Y)=g(X,Y)-\eta(X)\eta(Y).\end{aligned}\tag{2.1}$$

AMS Subject Classification (1991): Primary 53 C 15, 53 C 25,
Key words and phrases: almost cosymplectic manifold, cosymplectic manifold, D-homothetic deformation

On such a manifold we may always define 2-form Φ by $\Phi(X,Y) = g(\phi X, Y)$. Then (M, ϕ, ξ, η, g) is said to be an almost cosymplectic manifold if the forms Φ and η are closed, i.e., if $d\Phi = 0$, $d\eta = 0$, where d is a exterior differentiation. On an almost cosymplectic manifold we define an operator h by $h = -\frac{1}{2}\mathcal{L}_\xi \phi$, where $\mathcal{L}$ denotes the Lie differentiation. Then we see that h is symmetric, h anti-commutes with ϕ (i.e., $\phi h + h\phi = 0$), $h\xi = 0$, $\nabla_X \xi = \phi h X$ and $\operatorname{Tr} h = 0$, where ∇ is the covariant differentiation with respect to g and $\operatorname{Tr} h$ is the trace of h (see [**2**]). From $\phi h \xi = 0$, we notice

$$(\nabla_Y(\phi h))\xi = -h^2 Y \tag{2.2}$$

$$(\nabla_\xi(\phi h))X = R(\xi, X)\xi - h^2 X, \tag{2.3}$$

where R is the curvature tensor ($R(X,Y) = [\nabla_X, \nabla_Y] - \nabla_{[X,Y]}$). Furthermore, the following are satisfied [**2**]:

$$g(R(Y,\xi)\xi, Z) + g(R(\phi Y, \xi)\xi, \phi Z) + 2g(hY, hZ) = 0 \tag{2.4}$$

$$g(Q\xi, \xi) = -\operatorname{Tr} h^2, \tag{2.5}$$

where Q is the Ricci operator. If an almost contact structure of an almost cosymplectic manifold is normal, then it is said to be a cosymplectic manifold. As it is known, an almost contact metric structure is cosymplectic if and only if both $\nabla\eta$ and $\nabla\phi$ vanish ([**3**]; see also [**2**] and [**5**]). However, if we have $\nabla\phi = 0$, then, we can easily get $\nabla\eta = 0$ by taking the covariant differentiation of $\phi\xi = 0$. In a cosymplectic manifold M with structure tensor (ϕ, ξ, η, g), from $\nabla\xi = 0$ we have

$$R(X,Y)\xi = 0 \tag{2.6}$$

for any vector fields X and Y on M, wherefrom

$$Q\xi = 0. \tag{2.7}$$

Using $\nabla\phi = 0$ and $R(X,Y)\phi Z = \nabla_X\nabla_Y(\phi Z) - \nabla_Y\nabla_X(\phi Z) - \nabla_{[X,Y]}\phi Z$, we find

$$R(X,Y)\phi Z = \phi R(X,Y)Z. \tag{2.8}$$

Thus, using the property of the curvature tensor, we get

$$R(\phi X, \phi Y)Z = R(X,Y)Z. \tag{2.9}$$

From (2.9), we find $R(\phi X, Y)Z = -R(X, \phi Y)Z$. Moreover we have

$$\phi Q = Q\phi, \tag{2.10}$$

where we used

$$\begin{aligned} g(Q\phi Y, \phi Z) &= \sum_{i=1}^{2n+1} g(R(E_i, \phi Y)\phi Z, E_i) = -\sum_{i=1}^{2n+1} g(R(\phi E_i, Y)\phi Z, E_i) \\ &= -\sum_{i=1}^{2n+1} g(\phi R(\phi E_i, Y)Z, E_i) = \sum_{i=1}^{2n+1} g(R(\phi E_i, Y)Z, \phi E_i) = g(QY, Z), \end{aligned}$$

where $\{E_i,\ 1 \leq i \leq 2n+1\}$ is a ϕ-basis ($E_{n+t} = \phi E_t,\ 1 \leq t \leq n;\ E_{2n+1} = \xi$).

By D we denote the distribution of an almost contact metric manifold M defined by $\eta = 0$. M is said to be of pointwise constant ϕ-sectional curvature if at any point $x \in M$, the sectional curvature $K(X, \phi X)$ is independent of the choice of non-zero $X \in D_x$, In this case, the ϕ-sectional curvature K is a function on M.

An almost contact metric manifold is said to be η-Einstein if $Q = aI + b\eta \otimes \xi$, where a and b are smooth functions on M. Especially if $b = 0$, then M is said to be Einstein.

On a $(2n+1)$-dimensional almost cosymplectic manifold M the Weyl conformal curvature tensor of M is the tensor field C of type (1,3) defined by

$$\begin{aligned} C(X,Y)Z &= R(X,Y)Z \\ &+ \frac{1}{2n-1}(g(QX,Z)Y - g(QY,Z)X + g(X,Z)QY - g(Y,Z)QX) \\ &- \frac{S}{2n(2n-1)}(g(X,Z)Y - g(Y,Z)X) \end{aligned} \tag{2.11}$$

for any vector fields X, Y and Z on M (where S is the scalar curvature). Moreover we put

$$c(X,Y) = (\nabla_X Q)Y - (\nabla_Y Q)X - \frac{1}{2(2n-1)}((\nabla_X S)Y - (\nabla_Y S)X). \tag{2.12}$$

Then it is well-known that a necessary and sufficent condition for M to be conformally flat is that $C = 0$ for $n > 3$ and $c = 0$ for $n = 3$ (C vanishes identically for $n = 3$).

3. *D*-homothetic deformations. Let M be an $(m+1)$-dimensional ($m = 2n$) almost cosymplectic manifold. Now we define a tensor field B^{ac} on M by

$$\begin{aligned} B^{ac}(X,Y) &= R(X,Y) + \phi hX \wedge \phi hY \\ &+ \frac{1}{2(m+4)}(QY \wedge X - (\phi Q\phi Y) \wedge X + \frac{1}{2}(\eta(Y)Q\xi \wedge X + \eta(QY)\xi \wedge X) \\ &- QX \wedge Y + (\phi Q \phi X) \wedge Y - \frac{1}{2}(\eta(X)Q\xi \wedge Y + \eta(QX)\xi \wedge Y) + (Q\phi Y) \wedge \phi X \\ &+ (\phi QY) \wedge \phi X - (Q\phi X) \wedge \phi Y - (\phi QX) \wedge \phi Y + 2g(Q\phi X, Y)\phi \\ &+ 2g(\phi QX, Y)\phi + 2g(\phi X, Y)\phi Q + 2g(\phi X, Y)Q\phi - \eta(X)QY \wedge \xi \\ &+ \eta(X)(\phi Q \phi Y) \wedge \xi + \eta(Y)QX \wedge \xi - \eta(Y)(\phi Q\phi X) \wedge \xi), \end{aligned} \tag{3.1}$$

where $(X \wedge Y)Z = g(Y,Z)X - g(X,Z)Y$ (c.f. [**4**]). Using (3.1), B^{ac} satisfies the following identities in an almost cosymplectic manifold M.

$$\begin{gathered} B^{ac}(X,Y)Z = -B^{ac}(Y,X)Z, \\ B^{ac}(X,Y)Z + B^{ac}(Y,Z)X + B^{ac}(Z,X)Y = 0 \\ g(B^{ac}(X,Y)Z, W) = -g(Z, B^{ac}(X,Y)W), \\ g(B^{ac}(X,Y)Z, W) = g(B^{ac}(Z,W)X, Y). \end{gathered} \tag{3.2}$$

If M is a cosymplectic manifold, then B^{ac} turns into the following B^c because of (2.7), (2.10) and (3.1).

$$B^c(X,Y) = R(X,Y) + \frac{1}{m+4}(QY \wedge X - QX \wedge Y + Q\phi Y \wedge \phi X - Q\phi X \wedge \phi Y + 2g(Q\phi X, Y)\phi + 2g(\phi X, Y)Q\phi + \eta(Y)QX \wedge \xi + \eta(X)\xi \wedge QY).$$

B^c is the main part of the contact Bochner curvature tensor (Matsumoto and Chuman [**4**]). Moreover, the following are satisfied in a cosymplectic manifold M.

$$\begin{aligned} B^{ac}(\xi,Y)Z = B^c(\xi,Y)Z = B^c(X,Y)\xi = B^{ac}(X,Y)\xi = 0 \\ B^{ac}(\phi X,\phi Y)Z = B^c(\phi X,\phi Y)Z = B^c(X,Y)Z = B^{ac}(X,Y)Z, \end{aligned} \tag{3.3}$$

where we used (2.4), (2.6), (2.8) and (2.9).

We consider a D-homothetic deformation $g^* = \alpha g + \alpha(\alpha-1)\eta \otimes \eta$, $\phi^* = \phi$, $\xi^* = \alpha^{-1}\xi$, $\eta^* = \alpha\eta$ on an almost cosymplectic manifold M, where α is a positive constant. For a D-homothetic deformation we say that $M(\phi,\xi,\eta,g)$ is D-homothetic to $M(\phi^*,\xi^*,\eta^*,g^*)$. It is easy to see that if an almost cosymplectic manifold $M(\phi,\xi,\eta,g)$ is D-homothetic to $M(\phi^*,\xi^*,\eta^*,g^*)$, then $M(\phi^*,\xi^*,\eta^*,g^*)$ is an almost cosymplectic manifold. Moreover if $M(\phi,\xi,\eta,g)$ is a cosymplectic manifold, then $M(\phi^*,\xi^*,\eta^*,g^*)$ is also a cosymplectic manifold. Denoting by W^i_{jk} the difference $\Gamma^{*i}_{jk} - \Gamma^i_{jk}$ of Christoffel symbols, by $\nabla_X\xi = \phi hX$ (hence $(\nabla_X\eta)Y = (\nabla_Y\eta)X$) we have in an almost cosymplectic manifold M [**6**]

$$W(X,Y) = \frac{\alpha-1}{\alpha}(\nabla_X\eta)(Y)\xi = \frac{\alpha-1}{\alpha}g(\phi hX, Y)\xi.$$

Putting this into

$$R^*(X,Y)Z = R(X,Y)Z + (\nabla_X W)(Z,Y) - (\nabla_Y W)(Z,X) + W(W(Z,Y),X) - W(W(Z,X),Y)$$

and using $\nabla_X\xi = \phi hX$, we find

$$R^*(X,Y)Z = R(X,Y)Z + \frac{\alpha-1}{\alpha}(g(Y,(\nabla_X(\phi h))Z)\xi - g(X,(\nabla_Y(\phi h))Z)\xi + g(Y,\phi hZ)\phi hX - g(X,\phi hZ)\phi hY). \tag{3.4}$$

Here, choosing ϕ^*-basis with respect to g^* and using (2.2) and (2.3), we get

$$\mathrm{Ric}^*(Y,Z) = \mathrm{Ric}(Y,Z) - \frac{\alpha-1}{\alpha}(g(R(Z,\xi)\xi,Y) + g(h^2Y,Z)), \tag{3.5}$$

where Ric is the Ricci curvature of M. From (3.5) we have

$$Q^*Y = \frac{1}{\alpha}QY - \frac{\alpha-1}{\alpha^2}\eta(QY)\xi - \frac{\alpha-1}{\alpha^2}(h^2Y - R(\xi,Y)\xi), \tag{3.6}$$

where we used $\eta(Q^*Y) = \alpha^{-2}\eta(QY)$. By virtue of (3.5) we find

$$S^* = \frac{1}{\alpha}S - 2\frac{\alpha-1}{\alpha^2}\mathrm{Ric}(\xi,\xi). \tag{3.7}$$

Moreover if we consider the D-homothetic deformation of $\mathcal{L}_\xi \phi$, we find

$$h^* = \frac{1}{\alpha} h, \tag{3.8}$$

wherefrom we get

$$\operatorname{Tr} h^{*^2} = \frac{1}{\alpha^2} \operatorname{Tr} h^2. \tag{3.9}$$

After a clumsy computations we obtain, by means of (2.4), (3.1), (3.4), (3.5), (3.6) and (3.8), the following

$$\begin{aligned}
\overset{*}{B}{}^{ac}(X,Y)Z &= B^{ac}(X,Y)Z + \frac{\alpha-1}{\alpha}(g(Y,(\nabla_X(\phi h))Z)\xi - g(X,(\nabla_Y(\phi h))Z)\xi) \\
&+ \frac{1}{2}\frac{\alpha-1}{\alpha}(\eta(X)g(Q\xi,\xi)g(Y,Z)\xi - \eta(Y)g(Q\xi,\xi)g(X,Z)\xi) \\
&+ \frac{3}{2}\frac{\alpha-1}{\alpha}(g(Y,Z)\eta(QX)\xi - g(X,Z)\eta(QY)\xi \\
&\qquad + \eta(X)\eta(Z)\eta(QY)\xi - \eta(Y)\eta(Z)\eta(QX)\xi) \\
&+ \frac{\alpha-1}{\alpha}(\eta(Q\phi X)g(\phi Y,Z)\xi - \eta(Q\phi Y)g(\phi X,Z)\xi - 2\eta(Q\phi Z)g(\phi X,Y)\xi).
\end{aligned} \tag{3.10}$$

Now we shall introduce the AC-contact Bochner curvature tensor in M by

$$AC(X,Y)Z = B^{ac}(X,Y)Z - \eta(B^{ac}(X,Y)Z)\xi. \tag{3.11}$$

In particular, if M is a cosymplectic manifold, by the definition of B^c, (3.2) and (3.3), we have $AC = B^c$.

THEOREM 3.1. *The AC-contact Bochner curvature tensor is invariant with respect to the D-homothetic deformation $M(\phi,\xi,\eta,g) \to M(\phi^*,\xi^*,\eta^*,g^*)$ on an almost cosymplectic manifold M.*

Proof. Using (3.10), we find

$$\begin{aligned}
\overset{*}{B}{}^{ac}(X,Y)Z - \eta^*(B^{ac}(X,Y)Z)\xi^* &= \overset{*}{B}{}^{ac}(X,Y)Z - \eta(\overset{*}{B}{}^{ac}(X,Y)Z)\xi \\
&= B^{ac}(X,Y)Z - \eta(B^{ac}(X,Y)Z)\xi.
\end{aligned}$$

Thus we get $AC^*(X,Y)Z = AC(X,Y)Z$.

4. Some results. We define $s^\sharp = \sum_{i,j=1}^{2n+1} g(R(E_i,E_j)\phi E_j, \phi E_i)$, where $\{E_i\}$ is an orthonormal frame.

LEMMA 4.1. [**5**]. *For each almost cosymplectic manifold M we have*

$$S - s^\sharp - g(Q\xi,\xi) + \frac{1}{2}\|\nabla\phi\|^2 = 0.$$

Using this lemma, we prove the following.

THEOREM 4.1. *Let M be an almost cosymplectic manifold with vanishing AC-contact Bochner curvature tensor. Then M is a cosymplectic manifold and the scalar curvature of M vanishes.*

Proof. Since the AC-contact Bochner curvature tensor of M vanishes, we have

$$g(B^{ac}(X,Y)Z,W) = \eta(B^{ac}(X,Y)Z)\eta(W). \tag{4.1}$$

Taking $X = E_i$, $Y = E_j$, $Z = \phi E_j$, $W = \phi E_i$ ($\{E_i\}$ is a ϕ-basis) into the each member of (4.1), using (3.1) and summing over i and j, we have

$$\sum_{i,j=1}^{2n+1} g(B^{ac}(E_i,E_j)\phi E_j, \phi E_i) = s^\sharp - \operatorname{Tr} h^2 - \frac{2(n+1)}{n+2}(S - g(Q\xi,\xi)) = 0. \tag{4.2}$$

On the other hand, using (3.1), (4.1) and (3.2), we find

$$\sum_{i=1}^{2n+1} g(B^{ac}(E_i,\xi)\xi, E_i) = \frac{2}{(n+2)} g(Q\xi,\xi) = \sum_{i=1}^{2n+1} \eta(B^{ac}(E_i,\xi)\xi)\eta(E_i) = 0. \tag{4.3}$$

Moreover, calculating $\sum_{i,j=1}^{2n+1} g(B^{ac}(E_i,E_j)E_j,E_i)$ by means of (3.1), and using (4.1), (3.2) and (4.3), we get

$$\begin{aligned}\sum_{i,j=1}^{2n+1} g(B^{ac}(E_i,E_j)E_j,E_i) &= -\frac{n}{(n+2)}S - \operatorname{Tr} h^2 + \frac{2}{(n+2)} g(Q\xi,\xi) \\ = \sum_{i,j=1}^{2n+1} \eta(B^{ac}(E_i,E_j)E_j)\eta(E_i) &= \frac{2}{(n+2)} g(Q\xi,\xi) = 0.\end{aligned} \tag{4.4}$$

By Lemma 4.1, (2.5), (4.2), (4.3) and (4.4) we obtain our result.

Now, let M be a conformally flat almost cosymplectic manifold of dimension $(2n+1) \geq 5$. Then the following identities are known (see (3.1) in [**2**] and (6.4) in [**5**]), that is,

$$\begin{aligned}(2n-3)(\operatorname{Ric}(X,X) &+ \operatorname{Ric}(\phi X,\phi X)) \\ &= -\frac{S}{n} - (2n-1)(\|(\nabla\phi)(X)\|^2 + \|hX\|^2)\end{aligned} \tag{4.5}$$

$$\frac{2n-2}{2n-1}S + \frac{2n-3}{2n-1}\|\nabla\xi\|^2 + \frac{1}{2}\|\nabla\phi\|^2 = 0, \tag{4.6}$$

where X is a vector such that $X \in D_x$, $\|X\| = 1$. Here, we get the following theorem.

THEOREM 4.2. *Let M^{2n+1} be a conformally flat almost cosymplectic manifold of dimension $(2n+1) \geq 5$. Then the following conditions are equivalent:* (1) *M is locally flat* (2) *The AC-contact Bochner curvature of M vanishes* (3) *M is cosymplectic* (4) *The Ricci curvature of M is flat* (5) *The scalar curvature of M vanishes*

Proof. (1) $\Rightarrow$ (2): From (4.5) we have $S = \mathrm{Ric}\,(X, X) = \mathrm{Ric}\,(\phi X, \phi X) = 0$. Thus M is cosymplectic, wherefrom $h = 0$, so that $B^{ac} = 0$. Therefore $AC = B^c = 0$.

(2) $\Rightarrow$ (3): This follows from Theorem 4.1.

(3) $\Rightarrow$ (4): By (4.6) we find $S = 0$, so that, from (4.5) we get $g(QX, X) = g(\phi Q \phi X, X)$ for $X \in D_x$. However, from (2.10) and (2.7) we obtain $g(QX, X) = 0$ for $X \in D$. Using the polarization identity, we have $g(QX, Y) = 0$ for any $X, Y \in D$. Moreover, by (2.7) we obtain $g(QX, Y) = 0$ for any vector field X and Y, that is, the Ricci curvature of M is flat.

(4) $\Rightarrow$ (5): Trivial.

(5) $\Rightarrow$ (1): Using (4.6), we see that M is cosymplectic. Therefore, from (4.5) we get $g(QX, X) = (\phi Q \phi X, X)$ for $X \in D_x$, so that the Ricci curvature of M is flat. By (2.11) we get our result.

Remark 4.1. Theorem 4.2 is a generalization of Theorem 6 in [**5**].

Next, we consider an almost cosymplectic manifold with constant ϕ-sectional curvature K. Suppose that X is a vector such that $X \in D_x$, $\|X\| = 1$. Then we have the following (see (2.3) and Remark 2.1 in [**2**]).

$$\mathrm{Ric}\,(X, X) + \mathrm{Ric}\,(\phi X, \phi X) = (n+1)K - \frac{3}{4}\|(\nabla \phi)(X)\|^2 - \frac{5}{4}\|hX\|^2 \tag{4.7}$$

$$\begin{aligned} S &= \mathrm{Ric}\,(\xi, \xi) + \sum_{\alpha} \mathrm{Ric}\,(e_\alpha, e_\alpha) + \sum_{\alpha} \mathrm{Ric}\,(\phi e_\alpha, \phi e_\alpha) \\ &= -\|h\|^2 + (n+1)nK - \frac{3}{4}\sum_{\alpha=1}^{n} \|(\nabla \phi)(e_\alpha)\|^2 - \frac{5}{4}\sum_{\alpha=1}^{n} \|he_\alpha\|^2. \end{aligned} \tag{4.8}$$

From (4.7) and (4.8) we have the following theorem.

THEOREM 4.3. *Let M be an almost cosymplectic manifold with constant ϕ-sectional curvature. Then a necessary and sufficent condition for M to be locally flat is that the AC-contact Bochner curvature of M vanishes.*

Proof. Suppose that the AC-contact Bochner curvature of M vanishes. Then, from Theorem 4.1 M is cosymplectic and $S = 0$. This result and (4.8) lead to $K = 0$. Therefore, by (4.7) it follows that $\mathrm{Ric}\,(X, Y) = 0$ for any vector fields X and Y. Considering $B^{ac} = B^c = 0$, we can see that M is locally flat.

Conversely, suppose that M is locally flat. Then $K = \mathrm{Ric}\,(X, Y) = 0$, so that, by (4.7) we see that M is cosymplectic, wherefrom $B^{ac} = B^c = 0$. Therefore $AC = 0$.

Last we consider an almost cosymplectic manifold with vanishing AC-contact Bochner curvature tensor. Then we obtain the following theorem.

THEOREM 4.4. *Let $M^{2n+1} (n \neq 1)$ be an almost cosymplectic manifold with vanishing AC-contact Bochner curvature tensor. Then the following conditions are* *equivalent:* (1) *M has a constant ϕ-sectional curvature* 0, (2) *M has a constant ϕ-sectional curvature,* (3) *M is Ricci flat,* (4) *M is η-Einstein,* (5) *M is locally flat* (6) *M is conformally flat.*

Proof. First of all, since the AC-contact Bochner curvature tensor of M vanishes, M is cosymplectic and $S=0$. Then:

(1) $\Rightarrow$ (2) trivial;

(2) $\Rightarrow$ (3) from (4.8) we have $K=0$, so that, by (4.7) we get the result;

(3) $\Rightarrow$ (4) trivial;

(4) $\Rightarrow$ (1) since M is η-Einstein, by two definitions of η-Einstein manifold and B^c, (2.7) and (2.10), we get

$$\begin{aligned} g(R(X,Y)Z,W) &= -\frac{a}{2n+4}(2g(X,Z)g(Y,W)-2g(X,W)g(Y,Z) \\ &+2g(\phi X,Z)g(\phi Y,W)-2g(\phi X,W)g(\phi Y,Z)+4g(\phi Z,W)g(\phi X,Y) \\ &+\eta(Y)\eta(Z)g(X,W)-\eta(Y)\eta(W)g(X,Z)+\eta(X)\eta(W)g(Y,Z) \\ &-\eta(X)\eta(Z)g(Y,W))-\frac{b}{2n+4}(g(X,Z)\eta(Y)\eta(W)-g(X,W)\eta(Y)\eta(Z) \\ &-g(Y,Z)\eta(X)\eta(W)+g(Y,W)\eta(X)\eta(Z)). \end{aligned} \tag{4.9}$$

Taking $X\in T_x(M)$ such that $\|X\|=1$, $X\perp\xi$, and calculating $g(R(X,\phi X)\phi X,X)$ by using (4.9), we get $g(R(X,\phi X)\phi X,X)=\frac{4}{n+2}a$. On the other hand, from $\mathrm{Ric}\,(X,Y)=ag(X,Y)+b\eta(X)\eta(Y)$ we find $S=(2n+1)a+b$. We also have $\mathrm{Ric}\,(\xi,\xi)=a+b$. However, by (2.7) we get $b=-a$. Thus $S=2na$, wherefrom we find $g(R(X,\phi X)\phi X,X)=\frac{2S}{n(n+2)}$, which completes this proof;

(5) $\Rightarrow$ (1): trivial;

(1) $\Rightarrow$ (5): from (4.7) we have $\mathrm{Ric}\,(X,Y)=0$ for any vector fields X and Y. Considering $B^c=0$, we get the result;

(6) $\Rightarrow$ (5): by (4.5) we see that $\mathrm{Ric}\,(X,Y)=0$ for any vector fields X and Y. Moreover $S=0$. Therefore, by (2.11) we get that M is locally flat;

(5) $\Rightarrow$ (6): it folows from (2.11).

Remark 4.2. The curvature of a Riemannian manifold is said to be harmonic if the diveregence of its curvature tensor is zero. It is well known that a Riemannian manifold has harmonic curvature, if the Ricci operator Q satisfies

$$(\nabla_X Q)Y=(\nabla_Y Q)X$$

for any vector fields X, Y (e.g., see [**1**]). Theorem 4.4 is also valid for a 3-dimensional almost cosymplectic manifold M^3. At first the equivalences (1)–(5) are also valid for a 3-dimensional almost cosymplectic manifold. Here, put that (7) M^3 has a harmonic curvature. Then, from (4.7) we have $\mathrm{Ric}\,(X,Y)=0$ for any vector fields X, Y. Thus (1) $\Rightarrow$ (7). By (4.8) we get (7) $\Rightarrow$ (1). Moreover, from (2.12) we obtain (7) $\Longleftrightarrow$ (6). Therefore for an almost cosymplectic manifold M^3 the equivalences (1)–(7) hold good.

Acknowledgement. I would like to express my hearty thanks to the referee.

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(Received 15 07 1994)
(Revised 28 12 1994)