and

$$\frac{d}{d\gamma}(\operatorname{Re}\lambda_2)\Big|_{\gamma=\gamma_c} = -1/2\,\frac{d}{d\gamma}(\lambda_* - a_1)\Big|_{\gamma=\gamma_c} = \operatorname{Re}\left(\frac{d}{d\gamma}\lambda_2\right)\Big|_{\gamma=\gamma_c} < 0.$$

This completes the proof.

Remark. Using the technique of [9], the Jacobian matrix M can be written in the diagonal form

$$\begin{vmatrix} \dot{y}_1 \\ \dot{y}_2 \\ \dot{y}_3 \end{vmatrix} = \begin{vmatrix} k_{11} & k_{12} & 0 \\ k_{21} & k_{22} & 0 \\ 0 & 0 & a_2 \end{vmatrix}.$$

where $k_{12} = -k_{21} = -\sqrt{a_2}$.

Now, using the substitution $\rho = \gamma - \gamma_c$, then $k_{11} = k_{22}$ at $\rho = 0$ and we can write (2.2) in the form

$$\dot{y} = \Phi(y, \rho), \quad \dot{\rho} = 0.$$

Then, a center manifold C exists for this canonical suspended system at $(Y, \rho) = (0, 0) \in R^3 \times R^1$ (see [1], [5], [7]).

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THE C-PROJECTIVE CURVATURE OF SOME REAL HYPERSURFACES IN COMPLEX SPACE FORMS

BY

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P. Matzeu and the present author have defined in [2] the C-projective curvature tensor field of a torsion free connection, adapted to a normal almost contact structure on an odd-dimensional manifold. In the case of a Sasakian manifold this C-curvature tensor field does vanish if ans only if the considered Sasakian manifold has constant φ-sectional curvature. In the present paper we study the C-projective curvature in the case of the normal almost contact structures induced on certain real haypersurfaces of complex space forms. Recall that a normal almost contact structure is induced on a real hypersurface of a Kaehlerian manifold if and only if the Weingarten maopping does commute with the linear operator defining the almost contact structure on the hypersurface. In this case the Weingarten mapping has at most three distinct eigenvalues (see [3], [6]). We show that the η-umbilical real hypersurfaces of the complex space forms are C-projectively flat i.e. their C-projective curvature tensor field vanishes. The normal almost contact real hypersurfaces of a complex space form for which the Weingarten mapping has exactly three distinct eigenvalues are never projectively flat. The manifolds and tensor fields considered in this paper are C^∞. The usual notations from the differential geometry are used throughout this paper.

1. Real hypersurfaces of complex space forms. Let $\bar{M}$ be a Kaehlerian manifold of complex dimension $n+1$. Denote by J the almost complex structure tensor field of $\bar{M}$ and let $\bar{g}$ be the metric tensor field of $\bar{M}$. Then

$$J^2 = -I, \quad \bar{g}(JX, JY) = \bar{g}(X, Y); \quad X, Y \in \mathcal{X}(\bar{M}) \tag{1}$$

and if $\bar{\nabla}$ is the Levi Civita connection of $\bar{g}$ we have

$$(\bar{\nabla}_X J)Y = 0; \quad X, Y \in \mathcal{X}(\bar{M}), \tag{2}$$

If $\bar{M} = \bar{M}^{n+1}(c)$ is an $(n+1)$-dimensional complex space form of constant holomorphic sectional curvature $4c$, the curvature tensor field $\bar{R}$ of $\bar{\nabla}$ is given by

$$\begin{aligned}\bar{R}_{XY}Z = c\{\bar{g}(Y, Z)X - \bar{g}(X, Z)Y + \bar{g}(JY, Z)JX - \bar{g}(JX, Z)JY - \\ -2\bar{g}(JX, Y)JZ\}.\end{aligned} \tag{3}$$

Consider $M \subset \bar{M}^{n+1}(c)$ a $(2n+1)$-dimensional real hypersurface in the complex space form $\bar{M}^{n+1}(c)$. Suppose M is orientable and let N be the unit normal of M in $\bar{M}^{n+1}(c)$. An almost contact structure (φ, ξ, η) is induced on M by defining (see [3], [6]):

$$\xi=-JN,\ \eta(X)=\bar{g}(X, \xi),\ JX=\varphi X+\eta(X)N,\ X\in\mathfrak{X}(M). \tag{4}$$

Thus we have

$$\eta(\xi)=1,\ \varphi^2=-I+\xi\otimes\eta,\ \varphi\xi=0,\ \eta\circ\varphi=0 \tag{5}$$

and if g is the Riemannian metric induced on M from $\bar{g}$ we have

$$g(\varphi X, \varphi Y)=g(x, y)-\eta(X)\eta(Y);\quad X, Y\in\mathfrak{X}(M). \tag{6}$$

Denote by A the Weingarten mapping associated with the unit normal N of M in $\bar{M}^{n+1}(c)$. Then the Gauss-Weingarten formulae are

$$\bar{\nabla}_X Y=\dot{\nabla}_X Y+g(AX, Y)N,\ \bar{\nabla}_X N=-AX. \tag{7}$$

Recall that $\dot{\nabla}$ is the Levi Civita connection of g and A is selfadjoint i.e.

$$g(AX, Y)=g(X, AY). \tag{8}$$

Remark that, due to the last relation (3) we have

$$\bar{g}(JX, Y)=g(\varphi X, Y),\ X, Y\in\mathfrak{X}(M) \tag{9}$$

thus $g(\varphi X, Y)$ is the restriction to M of the fundamental 2-form $\bar{g}(JX, Y)$ of $\bar{M}^{n+1}(c)$. The Gauss-Codazzi compatibility relations are written as follows

$$\begin{aligned}\dot{R}_{XY}Z=c\{&g(Y, Z)X-g(X, Z)Y-g(\varphi X, Z)\varphi Y+g(\varphi Y, Z)\varphi X-\\ &-2g(\varphi X, Y)\varphi Z\}+g(AY, Z)AX-g(AX, Z)AY\\ (\dot{\nabla}_X A)Y-(\dot{\nabla}_Y A)X&=c\{\eta(X)\varphi Y-\eta(Y)\varphi X-2g(\varphi X, Y)\xi\}\end{aligned} \tag{10}$$

where $\dot{R}$ is the curvature tensor field of $\dot{\nabla}$.

Using the Gauss-Weingarten formulae (7) and the formulae (4) defining the almost contact structure (φ, ξ, η) we get

$$\dot{\nabla}_X\xi=\varphi AX,\ (\dot{\nabla}_X\eta)(Y)=g(\varphi AX, Y),\ (\dot{\nabla}_X\varphi)Y=\eta(Y)AX-g(AX, Y)\xi. \tag{11}$$

Remark that, generally, the almost contact metric structure (φ, ξ, η, g) is not Sasakian. Moreover, in order the almost contact structure (φ, ξ, η) be normal the Weingarten mapping must satisfy a certain special condition.

Proposition 1. [3]. *The almost contact structure (φ, ξ, η) is normal if and only if*

$$\varphi A=A\varphi. \tag{12}$$

The proof is got by a straightforward computation using the expression

$$N(X, Y)=[\varphi X, \varphi Y]-\varphi[\varphi X, Y]-\varphi[X, \varphi Y]-h[X, Y]+d\eta(X, Y)\xi \tag{13}$$

of the normality tensor field of (φ, ξ, η). In the expression of the tensor field N we have used the notation

$$h=I-\xi\otimes\eta=-\varphi^2. \tag{14}$$

Remark that h is a projection operator on $H=\operatorname{Ker}\eta=\operatorname{Im}\varphi$ and its kernel is $V=$ the trivial line bundle spanned by ξ. We have

$$h^2=h,\ h\varphi=\varphi h=\varphi,\ v^2=v,\ vh=hv=0,\ \varphi v=v\varphi=0 \tag{15}$$

where $v=\xi\otimes\eta$.

From now on we shall suppose that the condition (12) is fulfilled, thus the almost contact structure (φ, ξ, η) is normal.

Proposition 2. *The exterior differential of the 1-form η is given by*

$$d\eta(X, Y)=2g(\varphi AX, Y),\ X, Y\in\mathfrak{X}(M). \tag{16}$$

Proof. By straightforward computation using

$$d\eta(X, Y)=(\dot{\nabla}_X\eta)(Y)-(\dot{\nabla}_Y\eta)(X).$$

Proposition 3. *The torsion free linear connection ∇ defined by*

$$\nabla_X Y=\dot{\nabla}_X Y+P(X, Y) \tag{17}$$

where

$$P(X, Y)=\eta(X)(\varphi Y-\varphi AY)+\eta(Y)(\varphi X-\varphi AX) \tag{18}$$

is adapted to the normal almost contact structure (φ, ξ, η).

Proof. Verify by a straightforward computation that ∇ has the properties.

$$\begin{gathered}\nabla_X\xi=\varphi X,\ (\nabla_X\eta)(Y)=g(\varphi AX, Y)=\frac{1}{2}d\eta(X, Y),\\ (\nabla_X\varphi)Y=\eta(Y)hX-g(\varphi AX, \varphi Y)\xi=\eta(Y)hX-\frac{1}{2}d\eta(X, \varphi Y)\xi\end{gathered} \tag{19}$$

These are just the conditions for ∇ to be adapted (see [1], [2]).

Remark that since the condition (12) is fulfilled by the Weingarten mapping A we get that ξ is an eigenvector of A

$$A\xi=\alpha\xi. \tag{20}$$

Then $\eta(AX)=\alpha\eta(X)$ for any vector field X on M. Moreover, using the Codazzi relation (10) we get that α is a constant and the Weingarten mapping satisfies the relation

$$A^2X-\alpha AX-c\ hX=0,\ X\in\mathfrak{X}(M) \tag{21}$$

from which we get that A has at most three distinct eigenvalues. Moreover these eigenvalues are constant (see [6] for the necessary proofs).

Proposition 4. *The covariant derivative of the Weingarten mapping A with respect to the Levi Civita connection $\dot{\nabla}$ is given by*

$$(\dot{\nabla}_X A)Y=-c\eta(Y)*X-cg(\varphi X, Y)\xi. \tag{22}$$

Proof. Using (20), (21) and the relation $\eta(AX)=\alpha\eta(X)$ we get

$$(\dot{\nabla}_X A)\xi=-c\varphi X,\quad \eta((\dot{\nabla}_X A)Y)=-cg(\varphi X, Y).$$

Thus we may write

$$(\mathring{\nabla}_X A)Y = -c\eta(Y)\varphi X - cg(\varphi X, Y)\xi + Q(X, Y), \tag{23}$$

where Q is a tensor field of type (1, 2) on M satisfying

$$\eta(Q(X, Y)) = 0, \quad Q(X, \xi) = 0 \tag{24}$$

i.e.

$$hQ(X, Y) = Q(X, Y), \quad Q(X, hY) = Q(X, Y)\ ; \quad X, Y \in \mathcal{X}(M). \tag{24'}$$

Next, using the Codazzi condition (10) we get

$$Q(X, Y) = Q(Y, X)\ ; \quad X, Y \in \mathcal{X}(M). \tag{25}$$

From the condition (12) fulfilled by A and φ it follows by a straightforward computation

$$Q(X, \varphi Y) = \varphi Q(X, Y). \tag{26}$$

Finally, using (16) and the property $d^2 = 0$ of the exterior differential we get

$$g(X, \varphi Q(Y, Z)) + g(Y, \varphi Q(Z, X)) + g(Z, \varphi Q(X, Y)) = 0. \tag{27}$$

Taking in (27) φZ for Z and using the properties (24'), (25), (26) it follows

$$g(Q(X, Y), Z) = g(Q(Y, Z), X) + g(Q(Z, X), Y). \tag{28}$$

Then, taking in (27) φX, φY, φZ for X, Y, Z respectively and using again (24'), (25), 26 we get

$$g(Q(X, Y), Z) + g(Q(Y, Z), X) + g(Q(Z, X), Y) = 0. \tag{29}$$

Then from (28), (29) we get $Q = 0$.

Proposition 5. *The covariant derivative of the 2-form $d\eta$ with respect to the adapted connection ∇ is given by*

$$\begin{aligned}(\nabla_Z d\eta)(X, Y) &= 2\eta(X)g(AZ, Y) - 2\eta(Y)g(AZ, X) = \\ &= -\eta(X)d\eta(\varphi Z, Y) + \eta(Y)d\eta(\varphi Z, X).\end{aligned} \tag{30}$$

Proof. Use the expression (16) of $d\eta$, the formula (17) defining ∇ and the result of the proposition 4.

Proposition 6. *The curvature tensor filed R of the adapted connection ∇ is given by*

$$\begin{aligned}R_{XY}Z = c\{&g(hY, Z)hX - g(hX, Z)hY + g(\varphi Y, Z)\varphi X - g(\varphi X, Z)\varphi Y - \\ &- 2g(\varphi X, Y)\varphi Z\} - g(\varphi AY, Z)(\varphi X - \varphi AX) + g(\varphi AX, Z)(\varphi Y - \\ &- \varphi AY) + 2g(\varphi AX, Y)(\varphi Z - \varphi AZ) + g(hAY, Z)hAX - \\ &- g(hAX, Z)hAY + \eta(Z)\{-\eta(X)hY + \eta(Y)hX\} + \{\eta(X)g(AY, Z) - \\ &- \eta(Y)g(AX, Z)\}\xi.\end{aligned} \tag{31}$$

Proof. Use the general formula

$$\begin{aligned}R_{XY}Z = \mathring{R}_{XY}Z + (\mathring{\nabla}_X P)(Y, Z) - (\mathring{\nabla}_Y P)(X, Z) + P(X, P(Y, Z)) - \\ - P(Y, P(X, Z)).\end{aligned} \tag{32}$$

Next compute

$$\begin{aligned}(\mathring{\nabla}_X P)(Y, Z) = g(\varphi AX, Y)(\varphi Z - \varphi AZ) + (2 - 2\alpha)\eta(Y)\eta(Z)AX - \\ - 2c\eta(Y)\eta(Z)hX + g(\varphi AX, Z)(\varphi Y - \varphi AY) + \{(\alpha - 1)\eta(Y)g(AX, Z) + \\ + (\alpha - 1)\eta(Z)g(AX, Y) + c\eta(Y)g(hX, Z) + c\eta(Z)g(hX, Y)\}\xi\end{aligned} \tag{33}$$

and

$$\begin{aligned}P(X, P(Y, Z)) = \eta(X)\eta(Y)\{hZ + 2hAZ - hA^2Z\} + \eta(X)\eta(Z)\{-hY - \\ - c\,hY + 2AY - \alpha AY + (\alpha^2 - 2\alpha)\eta(Y)\xi\}.\end{aligned} \tag{34}$$

Finally, using (33), (34) and the expression (10) of R we get (31) after a quite long computation.

2. The C-projective curvature of the normal almost contact hypersurfaces in $\overline{M}^{n+1}(c)$. Let ∇ be a torsion free connection adapted to the normal almost contact structure (φ, ξ, η) on the $(2n+1)$-dimensiond manifold M; $(n > 1)$. (see [1], [2]). Then the C-projective curvature tensor field W of ∇ is given by

$$\begin{aligned}W_{XY}Z = hR_{XY}Z + \{L(X, Y) - L(Y, X)\}hZ + \{L(X, Z) + \eta(X)\eta(Z)\}hY - \\ - \{L(Y, Z) + \eta(Y)\eta(Z)\}hX - \{L(X, \varphi Y) - L(Y, \varphi X) + d\eta(X, Y)\}\varphi Z - \\ - \left\{L(X, \varphi Z) + \frac{1}{2}d\eta(X, Z)\right\}\varphi Y + \left\{L(Y, \varphi Z) + \frac{1}{2}d\eta(Y, Z)\right\}\varphi X\end{aligned} \tag{35}$$

where

$$\begin{aligned}L(X, Y) = \frac{1}{2n+2}\Big\{&S(X, hY) + d\eta(X, \varphi Y) + \frac{1}{4n^2 - 1}\{S(hX, Y) + \\ &+ S(hY, X) - S(\varphi X, \varphi Y) - S(\varphi Y, \varphi X)\}\Big\}\end{aligned} \tag{36}$$

and S is the Ricci tensor field of ∇ : $S(X, Y) = \operatorname{trace}(Z \to R_{ZX}Y)$

Recall that W has the properties

$$W_{XY}\xi = 0, \quad \eta(W_{XY}Z) = 0, \quad W_{XY}\varphi Z - \varphi W_{XY}Z = 0$$

$\operatorname{trace} W_{XY} = \operatorname{trace} \varphi W_{XY} = \operatorname{trace}(Z \to W_{ZX}Y) = \operatorname{trace}(Z \to \varphi W_{ZX}Y) = 0$ and it is invariant under the C-projective transformation of the connection ∇.

Suppose that M is a normal almost contact hypersurface in the complex space form $\overline{M}^{n+1}(c)$. Then using the results from the first section we get

$$S(X, Y) = (2n+4)cg(hX, Y) + (\alpha + \operatorname{tr} A - 2)g(hAX, Y) + 2n\eta(X)\eta(Y) \tag{37}$$

where $\operatorname{tr} A$ denotes the trace of the Weingarten mapping A. Thus S is symmetric and

$$\begin{aligned}(2n+2)L(X, Y) &= S(hX, Y) + g(hX, Y) = \\ &= 2c(n+2)g(hX, Y) + (\alpha + \operatorname{tr} A)g(hAX, Y).\end{aligned} \tag{38}$$

Next we get by a straightforward computation the expression of W

$$\begin{aligned}W_{XY}Z = \frac{c}{n+1}\{&g(hX, Z)hY - g(hY, Z)hX + g(\varphi X, Z)\varphi Y - \\ &- g(\varphi Y, Z)\varphi X + 2g(\varphi X, Y)\varphi Z\} + \frac{\alpha + \operatorname{tr} A}{2n+2}\{g(hAX, Z)hY -\end{aligned} \tag{39}$$

$$-g(hAY,Z)hX+g(\varphi AX,Z)\varphi Y-g(\varphi AY,Z)\varphi X+2g(\varphi AX,Y)\varphi Z\}+$$
$$(39)\qquad +g(hAY,Z)hAX-g(hAX,Z)hAY+g(\varphi AY,Z)\varphi AX-$$
$$-g(\varphi AX,Z)\varphi AY-2g(\varphi AX,Y)\varphi AZ.$$

Now we get our main result.

Theorem 7. *If M is a totally η-umbilical real hypersurface in the complex space form $\bar{M}^{n+1}(c)$ then it is C-projectively flat.*

Proof. The hypersurface M is totally η-umbilical if the Weingarten mapping A has the expression

$$AX=aX+b\eta(X)\xi$$

where a, b are scalar functions.

Then A satisfies the condition (12) and it has only two distinct eigenvalues. One of them is $\alpha=a+b$, the second one is a and using (21) we must have $ab=-c$. It follows that a, b are constant, $\operatorname{tr}A=(2n+1)a+b$ and using (39) we get $W=0$.

Remark. In the general case where M is a normal almost contact hypersurface in $\bar{M}^{n+1}(c)$ for which A has three distinct eigenvalues α, λ, μ, we must have

$$(40)\qquad \lambda+\mu=\alpha,\quad \lambda\mu=-c$$

thus λ, μ are constant. If X is an eigenvector of A corresponding to λ, then φX is again an eigenvector corresponding to λ, thus the multiplicity of λ must be an even number. Denote by $2p$ the multiplicity of λ. Then the multiplicity of μ is $2(n-p)$ and $\operatorname{tr}A=\alpha+2p\lambda+2(n-p)\mu$. If X, Y, Z are eigenvectors of A corresponding to λ the condition $W_{XY}Z=0$ is reduced to

$$2(2c+\alpha\lambda)\ (p-n)=0.$$

Since A must have three distinct eigenvalues $p\neq n$, thus $\alpha\lambda+2c=0$ and $4c+\alpha^2=0$. If $c>0$ it follows $W\neq 0$. If $c<0$ and $\alpha^2+4c=0$, take X, Y, Z eigenvectors of A corresponding to $\mu\neq 0$. Then we get $\alpha\mu+2c=0$ thus $\lambda=\mu$. We may conclude that the normal almost contact hypersurfaces of the complex space forms $\bar{M}^{n+1}(c)$ for which the Weingarten mapping has three distinct eigenvalues cannot be C-projectively flat.

Examples of normal almost contact hypersurfaces in complex space forms are obtained as follows. Consider $\bar{M}^{n+1}(1)=CP^{n+1}$ the complex projective space of constant holomorphic curvature 4. It is obtained from the unit sphere $S^{2n+3}\subset C^{n+2}$ by the usual projection $\pi: S^{2n+3}\to CP^{n+1}$, $\pi(z)=[z]=\{e^{i\theta}z;\ \theta\in R,\ z\in S^{2n+3}\}$. Next let $M_0'(2n+2, r)\subset S^{2n+3}$ be the hypersurface of S^{2n+3} defined by

$$\sum_{k=0}^{n}|z_k|^2=r|z_{n+1}|^2,\quad \sum_{k=0}^{n+1}|z_k|^2=1.$$

Then $M_0(2n+1, r)=\pi(M_0'(2n+2, r))\subset CP^{n+1}$ is a connected compact real hypersurface for which A has two constant eigenvalues. Namely $M_0(2n+1, r)$ is the geodesic hypersphere in CP^{n+1} and, according to the theorem 7 it is C-projectively flat.

In the case of the hypersurface $M'(2n+2, m, s)\subset S^{2n+3}$ defined by

$$\sum_{k=0}^{m}|z_k|^2=s\sum_{j=m+1}^{n+1}|z_j|^2,\quad \sum_{k=0}^{n+1}|z_k|^2=1$$

the projection in CP^{n+1} is $M(2n+1, m, s)=\pi(M'(2n+2, m, s))$; this is a real normal almost contact hypersurface in CP^{n+1} for which A has three distinct eigenvalues. Thus $M(2n+1, m, s)$ is never C-projectively flat.

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