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PURE MATHEMATICS | RESEARCH ARTICLE

Hemi-slant submanifolds of cosymplectic manifolds

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Abstract: In this paper, we study the hemi-slant submanifolds of cosymplectic manifolds. Necessary and sufficient conditions for distributions to be integrable are worked out. Some important results are obtained in this direction. We study the geometry of leaves of hemi-slant submanifolds.

Subjects: Advanced Mathematics; Geometry; Mathematics & Statistics; Science

Keywords: cosymplectic manifolds; hemi-slant submanifolds; slant submanifolds

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1. Introduction

In 1990, Chen introduced the notion of slant submanifold, which generalizes holomorphic and totally real submanifolds (1990). After that many research articles have been published by different geometers in this direction for different ambient spaces (Carriazo, 2002; Gupta, Haider, & Shahid, 2004).

Lotta introduced the notion of slant immersions of a Riemannian manifolds into an almost contact metric manifolds (1996). After these submanifolds were studied by Cabrerizo, Carriazo, Fernandez, and Fernandez in the setting of Sasakian manifolds (2000). Papaghiuc (2009) defines the semi-slant submanifolds as a generilization of slant submanifolds. Bi-slant submanifolds of an almost Hermitian manifold were introduced as natural generalization of semi-slant submanifolds by Carriazo (2000). One of the classes of bi-slant submanifolds is that of anti-slant submanifolds which are studied by Carriazo (2000) but the name anti-slant seems to refer that it has no slant factor, so

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PUBLIC INTEREST STATEMENT

In the modern era of mathematics, the topic "Geometry of Submanifolds" has become a very rich area of research for its applications in applied mathematics as well as in theoretical physics. The contributions of this paper would be interesting to researchers in differential geometry and other related fields for further work in this direction. In this work, we obtain the integrability of distributions and also study the geometry of leaves of distributions of hemi-slant submanifolds of cosymplectic manifolds.

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Sahin (2009) gives the name of hemi-slant submanifolds instead of anti-slant submanifolds. Khan and Khan (2000) studied the hemi-slant submanifolds of Sasakian manifolds.

In this paper, we study the hemi-slant submanifolds of cosymplectic manifolds. In Section 2, we collect the basic formulae and definitions for a cosymplectic manifolds and their submanifolds for ready references. In section 3, we study the hemi-slant submanifolds of cosymplectic manifolds. We obtain the integrability conditions of the distributions which are involved in the definition. Also we study the geometry of leaves of distributions.

2. Preliminaries

Let N be a $(2m + 1)$-dimensional almost contact metric manifold with structure (ϕ, ξ, η, g) where ϕ is a tensor field of type (1, 1), ξ a vector field, η is a one form and g is the Riemannian metric on N. Then they satisfy

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

These conditions also imply that

$$\phi\xi = 0, \quad \eta(\phi X) = 0, \quad \eta(X) = g(X, \xi), \tag{2}$$

and

$$g(\phi X, Y) + g(X, \phi Y) = 0, \tag{3}$$

for all vector fields X, Y in TN. Where TN denotes the Lie algebra of vector fields on N. An almost contact metric manifold is called a cosymplectic manifold if

$$(\overline{\nabla}_X \phi) = 0, \quad \overline{\nabla}_X \xi = 0, \tag{4}$$

where $\overline{\nabla}$ denotes the Levi-Civita connection of (N, g).

Throughout, we denote by N a cosymplectic manifold, M a submanifold of N and ξ a structure vector field tangent to M. A and h denote the shape operator and second fundamental form of immersion of M into N. If ∇ is the induced connection on M, the Gauss and Weingarten formulae of M into N are then given, respectively, by

$$\overline{\nabla}_X Y = \nabla_X Y + h(X, Y), \tag{5}$$

$$\overline{\nabla}_X V = -A_V X + \nabla_X^\perp V, \tag{6}$$

for all vector fields X, Y on TM and V on $T^\perp M$, where $\nabla^\perp$ denotes the connection on the normal bundle $T^\perp M$ of M. The shape operator and the second fundamental form are related by

$$g(A_V X, Y) = g(h(X, Y), V). \tag{7}$$

The mean curvature vector is defined by

$$H = \frac{1}{n} trace(h) = \frac{1}{n} \sum_{i=1}^{n} h(e_i, e_i), \tag{8}$$

where n is the dimension of M and $\{e_1, e_2, \ldots, e_n\}$ is the local orthonormal frame of M.

For any $X \in TM$, we can write

$$\phi X = TX + FX, \tag{9}$$

where *TX* and *FX* are the tangential and normal components of ϕX, respectively.

Similarly for any $V \in T^\perp M$, we have

$$\phi V = tV + fV, \tag{10}$$

where *tV* and *fV* are the tangential and normal components of ϕV, respectively.

The covariant derivative of the tensor fields *T*, *F*, *t*, and *f* are defined by the following

$$(\nabla_X T)Y = \nabla_X TY - T\nabla_X Y, \tag{11}$$

$$(\nabla_X F)Y = \nabla_X^\perp FY - F\nabla_X Y, \tag{12}$$

$$(\nabla_X t)V = \nabla_X tV - t\nabla_X^\perp V, \tag{13}$$

and

$$(\nabla_X f)V = \nabla_X^\perp fV - f\nabla_X^\perp V, \tag{14}$$

for all *X*, $Y \in TM$, and $V \in T^\perp M$.

A submanifold *M* of an almost contact metric manifold *N* is said to be totally umbilical if

$$h(X, Y) = g(X, Y)H, \tag{15}$$

where *H* is the mean curvature vector. If $h(X, Y) = 0$ for any $X, Y \in TM$, then *M* is said to be totally geodesic and if $H = 0$, then *M* is said to be a minimal submanifold.

Lotta has introduced the notion of slant immersion of a Riemannian manifold into an almost contact metric manifold (1996) and slant submanifolds in Sasakian manifolds have been studied by Cabrerizo et al. (2000).

For any $x \in M$ and $X \in T_x M$, if the vectors *X* and ξ are linearly independent, the angle denoted by $\theta(X) \in [0, \frac{\pi}{2}]$ between ϕX and $T_x M$ is well defined. If $\theta(X)$ does not depend on the choice of $x \in M$ and $X \in T_x M$, we say that *M* is slant in *N*. The constant angle θ is then called the slant angle of *M* in *N*. The anti-invariant submanifold of an almost contact metric manifold is a slant submanifold with slant angle $\theta = \frac{\pi}{2}$ and an invariant submanifold is a slant submanifold with the slant angle $\theta = 0$. If the slant angle θ of *M* is different from 0 and $\frac{\pi}{2}$, then it is called a proper slant submanifold. If *M* is a slant submanifold of an almost contact manifold then the tangent bundle *TM* of *M* is decomposed as

$$TM = D \oplus \langle \xi \rangle,$$

where $\langle \xi \rangle$ denotes the distribution spanned by the structure vector field ξ and *D* is a complementary distribution of $\langle \xi \rangle$ in *TM*, known as the slant distribution. For a proper slant submanifold *M* of an almost contact manifold *N* with a slant angle θ, Lotta (1996) proved that

$$T^2 X = -\cos^2 \theta(X - \eta(X)\xi), \quad \forall X \in TM.$$

Cabrerizo et al. (2000) extended the above result into a characterization for a slant submanifold in a contact metric manifold. In fact, they obtained the following crucial theorems.

THEOREM 2.1 *(Cabrerizo et al., 2000) Let M be a slant submanifold of an almost contact metric manifold N such that $\xi \in TM$. Then M is slant submanifold if and only if there exists a constant $\lambda \in [0, 1]$ such that*

$$T^2 = -\lambda(I - \eta \otimes \xi),$$

furthermore, in such case, if θ is the slant angle of M, then $\lambda = \cos^2 \theta$.

THEOREM 2.2 *(Cabrerizo et al., 2000) Let M be a slant submanifold of an almost contact metric manifold $\overline{M}$ with slant angle θ. Then for any $X, Y \in TM$, we have*

$$g(TX, TY) = \cos^2\theta\{g(X, Y) - \eta(X)\eta(Y)\},$$

and

$$g(FX, FY) = \sin^2\theta\{g(X, Y) - \eta(X)\eta(Y)\}.$$

3. Hemi-slant submanifolds of cosymplectic manifolds

In the present section, we introduce the hemi-slant submanifolds and obtain the necessary and sufficient conditions for the distributions of hemi-slant submanifolds of cosymplectic manifolds to be integrable. We obtain some results for the leaves of distributions.

Definition 3.1 Let *M* be submanifold of an almost contact metric manifold *N*, then *M* is said to be a hemi-slant submanifold if there exist two orthogonal distributions D^θ and $D^\perp$ on *M* such that

(i) $TM = D^\theta \oplus D^\perp \oplus \langle \xi \rangle$

(ii) D^θ is a slant distribution with slant angle $\theta \neq \frac{\pi}{2}$,

(iii) $D^\perp$ is a totally real, that is $JD^\perp \subseteq T^\perp M$,

It is clear from above that CR-submanifolds and slant submanifolds are hemi-slant submanifolds with slant angle $\theta = \frac{\pi}{2}$ and $D^\theta = 0$, respectively.

In the rest of this paper, we use *M* a hemi-slant submanifold of almost contact metric manifold *N*.

On the other hand, if we denote the dimensions of the distributions $D^\perp$ and D^θ by m_1 and m_2, respectively, then we have the following cases:

(1) If $m_2 = 0$, then *M* is anti-invariant submanifold,

(2) If $m_1 = 0$ and $\theta = 0$, then *M* is an invariant submanifold,

(3) If $m_1 = 0$ and $\theta \neq 0$, then *M* is a proper slant submanifold with slant angle θ,

(4) if $m_1, m_2 \neq 0$ and $\theta \in (0, \frac{\pi}{2})$, then *M* is a proper hemi-slant submanifold.

Suppose *M* to be a hemi-slant submanifold of an almost contact metric manifold *N*, then for any $X \in TM$, we put

$$X = P_1X + P_2X + \eta(X)\xi, \tag{16}$$

where P_1 and P_2 are projection maps on the distribution $D^\perp$ and D^θ. Now operating ϕ on both sides of (16), we arrive at

$$\phi X = \phi P_1 X + \phi P_2 X + \eta(X)\phi\xi,$$

Using (2) and (9), we have

$$TX + FX = FP_1X + TP_2X + FP_2X,$$

It is easy to see on comparing that

$$TX = TP_2X, \quad FX = FP_1X + FP_2X,$$

If we denote the orthogonal complement of ϕTM in $T^\perp M$ by μ, then the normal bundle $T^\perp M$ can be decomposed as

$$T^\perp M = F(D^\perp) \oplus F(D^\theta) \oplus \mu. \tag{17}$$

As $F(D^\perp)$ and $F(D^\theta)$ are orthogonal distributions. Now g(Z,W) = 0 for each $Z \in D^\perp$ and $W \in D^\theta$. Thus, by (1), (3) and (9), we have

$$g(FZ, FX) = g(\phi Z, \phi X) = g(Z, X) = 0, \tag{18}$$

which shows that the distributions $F(D^\perp)$ and $F(D^\theta)$ are mutually perpendicular. In fact, the decomposition (17) is an orthogonal direct decomposition. Following lemma's can be easily calculated.

LEMMA 3.2   *Let M be a hemi-slant submanifolds of a cosymplectic manifold N. Then we have*

$$\nabla_X TY - A_{FY}X = T\nabla_X Y + th(X, Y)$$

and

$$h(X, TY) + \nabla_X^\perp FY = F\nabla_X Y + fh(X, Y)$$

for all $X, Y \in TM$.

LEMMA 3.3   *Let M be a hemi-slant submanifolds of a cosymplectic manifold N. Then we have*

$$\nabla_X tV - A_{FV}X = -TA_V X + t\nabla_X^\perp V$$

and

$$h(X, tV) + \nabla_X^\perp FV = -fA_V Y + f\nabla_V^\perp V.$$

for all $X \in TM$ and $V \in T^\perp M$.

LEMMA 3.4   *Let M be a hemi-slant submanifolds of a cosymplectic manifold N, then*

$$h(X, \xi) = 0, \quad h(TX, \xi) = 0 \quad \nabla_X \xi = 0,$$

for all $X, Y \in TM$.

Proof   We know that for $\xi \in TM$, we have

$$\overline{\nabla}_X \xi = \nabla_X \xi + h(X, \xi)$$

From (4), it follows that

$$\nabla_X \xi + h(X, \xi) = 0.$$

Thus, result follows directly from the above equation.   □

THEOREM 3.5 *Let M be a hemi-slant submanifold of a cosymplectic manifold N, Then*

$$A_{\phi Z}W = A_{\phi W}Z,$$

for all $Z, W \in D^\perp$.

Proof For $Z \in TM$, using (7), we have

$$g(A_{\phi W}Z, X) = g(h(Z, X), \phi W)$$
$$= -g(\phi h(Z, X), W)$$
$$= -g(\phi \overline{\nabla}_X Z, W) - g(\phi \nabla_X Z, W)$$
$$= -g(\phi \overline{\nabla}_X Z, W).$$

Using (4), we have

$$g(A_{\phi W}Z, X) = -g(\overline{\nabla}_X \phi Z - (\overline{\nabla}_X \phi)Z, W)$$
$$= -g(\overline{\nabla}_X \phi Z, W)$$
$$= -g(-A_{\phi Z}X + \nabla_X^{\perp}\phi Z, W)$$
$$= g(A_{\phi Z}X, W).$$

By use of $h(X, Y) = h(Y, X)$, we arrive at

$$g(A_{\phi W}Z, X) = g(A_{\phi Z}W, X)$$

Hence the result. □

THEOREM 3.6 *Let M be a hemi-slant submanifolds of a cosymplectic manifold N. Then the distribution $D^{\perp}$ is integrable if and only if*

$$A_{FZ}W = A_{FW}Z,$$

(19)

for any Z, W in $D^{\perp}$.

Proof For $Z, W \in D^{\perp}$, using (4), we have

$$(\overline{\nabla}_Z \phi)W = 0,$$

which implies that

$$\overline{\nabla}_Z \phi W - \phi \overline{\nabla}_Z W = 0.$$

Using (5), (6), (7), and (8), we have

$$\overline{\nabla}_Z FW - T\overline{\nabla}_Z W - F\overline{\nabla}_Z W = 0,$$

or

$$-A_{FW}Z + \nabla_Z^{\perp}FW - T\nabla_Z W + th(Z, W) - F\nabla_Z W - fh(Z, W) = 0,$$

(20)

Comparing the tangential components of (20), we have

$$A_{FW}Z + T\nabla_Z W + th(Z, W) = 0,$$

Interchange Z and W, and subtract, we have

$$T[Z, W] = A_{FW}Z - A_{FZ}W.$$

Thus $[Z, W] \in D^{\perp}$ if and only if (19) satisfies. □

THEOREM 3.7 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. Then the distribution $D^\theta \oplus D^\perp$ is integrable iff*

$g([X, Y], \xi) = 0,$

for all $X, Y \in D^\theta \oplus D^\perp$

Proof For $X, Y \in D^\theta \oplus D^\perp$, we have

$$g([X, Y], \xi)] = g(\nabla_X Y, \xi) - g(\nabla_Y X, \xi)$$
$$= -g(\nabla_X \xi, Y) + g(\nabla_Y \xi, X).$$

Using (4), we have

$g([X, Y], \xi) = 0.$ □

THEOREM 3.8 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. Then the anti-invariant distribution $D^\perp$ is integrable if and only if*

$$T\nabla_Z W = T\nabla_W Z,$$

(21)

for any $Z, W \in D^\perp$.

Proof For $Z, W \in D^\perp$, we have

$(\overline{\nabla}_Z \phi)W = 0,$

or

$\overline{\nabla}_Z \phi W - \phi \overline{\nabla}_Z W = 0,$

whereby we have

$\overline{\nabla}_Z FW - \phi(\nabla_Z W + h(W, Z)) = 0,$

or

$-A_{FW}Z + \overline{\nabla}_Z^\perp FW - T\nabla_Z W - F\nabla_Z W - th(Z, W) - fh(Z, W) = 0.$

Comparing the tangential components we have,

$-A_{FW}Z - T\nabla_Z W - th(Z, W) = 0.$

Using Theorem 3.5, we conclude that

$T[Z, W] = A_{FW}Z + T\nabla_Z W + th(Z, W).$

For $[Z, W] \in D^\perp$, we have $\phi[Z, W] = F[Z, W]$ because the tangential component of $\phi[Z, W]$ is zero. Thus, we have

$A_{FW}Z + T\nabla_Z W + th(Z, W) = 0.$

(22)

Similarly, we have

$$A_{FZ}W + T\nabla_W Z + th(W, Z) = 0. \tag{23}$$

Whereby use of Theorem 3, (22), and (23), we have

$$T\nabla_Z W = T\nabla_W Z$$

Thus the anti-invariant distribution $D^\perp$ is integrable if and only if (21) satisfies. □

THEOREM 3.9 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. Then the slant distribution D^θ is integrable iff*

$$h(X, TY) - h(Y, TX) + \nabla_X^\perp FY - \nabla_Y^\perp FX \in \mu \oplus F(D^\theta),$$

for any $X, Y \in D^\theta$.

Proof For $Z \in D^\perp$ and $X, Y \in D^\theta$, we have

$$g([X, Y], Z) = g(\overline{\nabla}_X Y - \overline{\nabla}_Y X, Z).$$

Using (1), (2), and (4), we get

$$g([X, Y], Z) = g(\phi\overline{\nabla}_X Y, \phi Z) - g(\phi\overline{\nabla}_Y X, \phi Z)$$

whereby use of (5), (6), we obtain

$$g([X, Y], Z) = g(h(X, TY) - h(Y, TX) + \nabla_X^\perp FY - \nabla_Y^\perp FX, \phi Z)$$

As $\phi X \in \phi(D^\perp)$ and $F(D^\theta)$ and $F(D^\perp)$ are orthogonal to each other in $T^\perp M$, thus we conclude the result. □

THEOREM 3.10 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. Then the slant distribution D^θ is integrable if and only if*

$$P_1\{\nabla_X TY - \nabla_Y TX - A_{FX}Y - A_{FY}X\} = 0,$$

for any $X, Y \in D^\theta$.

Proof We denote by P_1 and P_2 the projections on $D^\perp$ and D^θ, respectively. For any vector fields $X, Y \in D^\theta$. Using equation (4), we have

$$(\overline{\nabla}_X \phi)Y = 0,$$

that is

$$(\overline{\nabla}_X \phi Y) - \phi\overline{\nabla}_X Y = 0.$$

Using equation (5), (6), and (9), we have

$$\overline{\nabla}_X TY + (\overline{\nabla}_X FY) - \phi(\nabla_X Y + h(X, Y)),$$

or

$$\nabla_X TY + h(X, TY) - A_{FY}X + \nabla_X^\perp FY - T\nabla_X Y - F\nabla_X Y - th(X, Y) - fh(X, Y) = 0. \tag{24}$$

Comparing the tangential components of (24), we have

$$\nabla_X TY - A_{FY}X - T\nabla_X Y - th(X, Y) = 0. \tag{25}$$

Replacing X and Y, we have

$$\nabla_Y TX - A_{FX}Y - T\nabla_Y X - th(Y, X) = 0. \tag{26}$$

From (25) and (26), we arrive at

$$T[X, Y] = \nabla_X TY - \nabla_Y TX + A_{FY}X - A_{FX}Y. \tag{27}$$

Applying P_1 to (27), we obtain the result. □

THEOREM 3.11 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. If the leaves of $D^{\perp}$ are totally geodesic in M, then*

$$g(h(X, Z), FW) = 0$$

for $X \in D^{\theta}$ and $Z, W \in D^{\perp}$.

Proof Since $(\overline{\nabla}_Z \phi)W = 0$. From (4), we have

$$\overline{\nabla}_Z \phi W = \phi \overline{\nabla}_Z W$$

Using (5), (6), and (9), we obtain

$$\nabla_Z TW + h(Z, TW) - A_{FW}Z + \nabla_Z^{\perp} FW = \phi \nabla_Z W + \phi h(Z, W).$$

For $X \in D^{\theta}$, we have

$$g(\nabla_Z TW, X) - g(A_{FW}Z, X) = g(\phi \nabla_Z W, X).$$

Therefore, we have

$$g(\nabla_Z TW, X) - g(\nabla_Z W, \phi X) = g(h(X, Z), FW). \tag{28}$$

The leaves of $D^{\perp}$ are totally geodesic in M, if for $Z, W \in D^{\perp}$, $\nabla_Z W \in D^{\perp}$. Therefore from (28), we get the result. □

THEOREM 3.12 *Let M be a hemi-slant submanifold of a cosymplectic manifold N. If the leaves of D^{θ} are totally geodesic in M, then*

$$g(h(X, Y), \phi Z) = 0$$

for $X, Y \in D^{\theta}$ and $Z \in D^{\perp}$.

Proof From (4), we know that $(\overline{\nabla}_X \phi)Y = 0$, then

$$\overline{\nabla}_X \phi Y = \phi \overline{\nabla}_X Y.$$

For $Z \in D^{\perp}$ and using (5), (6), and (9), we get

$$g(\nabla_X \phi Y, Z) - g(\phi \nabla_X Y, Z) = g(h(X, Y), \phi Z).$$

Therefore from above equation, we get the result. □

Theorem 3.13   *Let M be a totally umbilical hemi-slant submanifold of a cosymplectic manifold N. Then at least one of the following holds*

(1) $dim(D^\perp) = 1$,

(2) $H \in \mu$,

(3) M is proper hemi-slant submanifold.

Proof   For a cosymplectic manifold, we have

$$(\overline{\nabla}_Z \phi)Z = 0,$$

for any $Z \in D^\perp$. Using (5), (6), and (9), we have

$$\overline{\nabla}_Z FZ - \phi(\nabla_Z Z + h(Z,Z)) = 0.$$

Whereby, we obtain

$$-A_{FZ}Z + \nabla_Z^\perp FZ - F\nabla_Z Z - th(Z,Z) - nh(Z,Z) = 0.$$

Comparing the tangential components, we have

$$A_{FZ}Z + th(Z,Z) = 0.$$

Taking inner product with $W \in D^\perp$, we obtain

$$g(A_{FZ}Z + th(Z,Z), W) = 0,$$

or

$$g(h(Z,W), FZ) + g(th(Z,Z), W) = 0.$$

Since M is totally umbilical submanifold, we obtain

$$g(Z,W)g(H,FZ) + g(Z,Z)g(tH,W) = 0.$$

The above equation has a solution if either $dim(D^\perp) = 1$ or $H \in \mu$ or $D^\perp = 0$, this completes the proof. □

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