PINCHING THEOREMS FOR TOTALLY REAL MINIMAL SUBMANIFOLDS IN $CP^n$

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Abstract. Let $M$ be an $n$-dimensional totally real minimal submanifold in $CP^n$. We prove that if $M$ is semi-parallel and the scalar curvature $\tau$, $-(n-1)(n-2)(n+1)/2 \leq \tau \leq 0$, then $M$ is an open part of the Clifford torus $T^n \subset CP^n$. If $M$ is semi-parallel and the scalar curvature $\tau$, $n(n-1) \leq \tau \leq n^2-3n+2/2$, then $M$ is an open part of the real projective space $RP^n$.

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1. Introduction. Among all submanifolds of an almost Hermitian manifold, there are two typical classes: one is the class of holomorphic submanifolds and, the other is the class of totally real submanifolds. A submanifold $M$ of an almost Hermitian manifold $\tilde{M}$ is called holomorphic (resp. totally real) if each tangent space of $M$ is mapped into itself (resp. the normal space) by the almost complex structure of $\tilde{M}$.

Given an isometric immersion $f : M \rightarrow \tilde{M}$, let $h$ be the second fundamental form and $\nabla$ the van der Waerden–Bortolotti connection of $M$. If $\nabla h = 0$, then $M$ is said to have parallel second fundamental form. The class of isometric immersions in a Riemannian manifold with parallel second fundamental form is very wide, as it is shown, for instance, in the classical paper of D. Ferus [8]. Certain generalisations of these immersions have been studied, obtaining classification theorems in some cases.

H. Naitoh [11] and M. Takeuchi [13] classified submanifolds in a real and complex space form with parallel second fundamental form. Among such examples, there exist three $n$-dimensional conformally flat totally real minimal submanifolds in a complex projective space $CP^n$ of constant holomorphic sectional curvature 4:

(i) a totally geodesic submanifold;
(ii) a flat torus;
(iii) a Riemannian product

\[ S_{1,n-1} : S^1(\sin a \cos a) \times S^{n-1}(\sin a), \]

where \( S^n(r) \) is an \( n \)-dimensional sphere with radius \( r \) and \( \tan a = \sqrt{n} \).

The purpose of this paper is to give the characterisation of (i) and (ii) of \( n \) dimension.

On the other hand, in [7], N. Ejiri studied four-dimensional compact orientable conformally flat totally real minimal submanifold in \( CP^4 \). Precisely, he proved the following theorem:

**Theorem A.** If \( M \) is four-dimensional compact, orientable and conformally flat and has non-negative Euler number and the scalar curvature \( \tau \), \( 0 \leq \tau \leq \frac{15}{2} \), then \( M \) is flat or locally isometric to \( S_{1,3} \).

In [12], D. Perrone considered six-dimensional case. Under the same conditions in Ejiri’s result, he obtained that if the scalar curvature \( \tau \), \( 0 \leq \tau \leq \frac{70}{5} \), then \( M \) is locally isometric to \( S_{1,5} \).

Recently, A. M. Li and G. Zhao [9] proved the following theorems:

**Theorem B.** Let \( M \) be an \( n \)-dimensional totally real minimal submanifold with constant sectional curvature \( c \) in \( CP^n \). Then \( M \) is either totally geodesic or flat.

**Theorem C.** Let \( M \) be an \( n \)-dimensional totally real minimal embedding submanifold in \( CP^n \) with constant sectional curvature. Then \( M \) is either an open part of the real projective space \( RP^n \subset CP^n \) or an open part of the Clifford torus \( T^n \subset CP^n \).

**Theorem D.** Let \( M \) be an \( n \)-dimensional totally real minimal submanifold with parallel second fundamental form in \( CP^n \). If \( \tau \leq 0 \) (namely \( ||h||^2 \geq n(n-1) \)), then \( M \) is an open part of the Clifford torus \( T^n \subset CP^n \).

Furthermore, in [4], J. Deprez defined the immersion to be *semi-parallel* if

\[ \bar{R}(X, Y) \cdot h = (\bar{\nabla}_X \bar{\nabla}_Y - \bar{\nabla}_Y \bar{\nabla}_X - \bar{\nabla}_{[X,Y]}h)h = 0 \quad (1) \]

holds for any vectors \( X, Y \) tangent to \( M \). The semi-parallelity condition is a local holonomy condition on the second fundamental form with respect to the connection \( \bar{\nabla} \), which is the induced connection on the tensor product of the Levi-Civita connection on the tangent bundle and the normal connection in the normal bundle of the submanifold \( M \). It is well known that if second fundamental form of \( M \) is parallel, then it is semi-parallel. But the converse is not necessary to be parallel. J. Deprez studied semi-parallel immersions in real space forms [4, 5]. In [10], Ü. Lumiste showed that a semi-parallel submanifold is the second-order envelope of the family of submanifolds with parallel second fundamental form. Later, studying hypersurfaces in the sphere and the hyperbolic space, F. Dillen showed that they are flat surfaces, hypersurfaces.
with parallel Weingarten endomorphism or rotation hypersurfaces of certain helices \([6]\).

In the present study, taking semi-parallelity condition instead of the parallelity of the second fundamental form of \(M\) in Li and Zhao’s \([9]\) result we obtain the following results:

**Theorem 1.** Let \(M\) be an \(n\)-dimensional totally real minimal submanifold in \(\mathbb{C}P^n\). If \(M\) is semi-parallel and the scalar curvature \(\tau\), \(n(n - 1) \leq \tau \leq \frac{n^2 - 3n + 2}{2},\) then \(M\) is an open part of real projective space \(\mathbb{R}P^n\).

**Theorem 2.** Let \(M\) be an \(n\)-dimensional totally real minimal submanifold in \(\mathbb{C}P^n\). If \(M\) is semi-parallel and the scalar curvature \(\tau\), \(-\frac{(n-1)(n-2)(n+1)}{2} \leq \tau \leq 0\), then \(M\) is an open part of the Clifford torus \(T^n \subset \mathbb{C}P^n\).

2. **Preliminaries.** Let \(M\) be an \(n\)-dimensional totally real submanifold of complex projective space \(\mathbb{C}P^n\); that is \(M\) is immersed in \(\mathbb{C}P^n\) and \(J(T_xM)\) is orthogonal to \(T_xM\) for all \(x \in M\), where \(J\) denotes the almost complex structure of \(\mathbb{C}P^n\) (see \([14]\) and \([15]\)).

We denote by \(\tilde{g}\) and \(g\) the Riemannian metric of \(\mathbb{C}P^n\) and \(M\), respectively. The Gauss and Weingarten formulas are given by

\[
\tilde{\nabla}_X Y = \nabla_X Y + h(X, Y)
\]

and

\[
\tilde{\nabla}_X \xi = -A_\xi X + D_X \xi,
\]

respectively, where \(\xi\) is a normal vector field and \(X, Y\) are tangent vector fields on \(M\); \(h\) is called the second fundamental form of \(M\). If \(h = 0\), then \(M\) is said to be totally geodesic. The mean curvature vector \(H\) of \(M\) is defined to be

\[
H = \frac{1}{n} \text{tr}(h).
\]

A submanifold \(M\) is said to be **minimal** if \(H = 0\) identically.

The covariant derivative \(\nabla h\) of \(h\) is defined by

\[
(\nabla_X h)(Y, Z) = \nabla_X^h(h(Y, Z)) - h(\nabla_X Y, Z) - h(Y, \nabla_X Z),
\]

where, \(\nabla h\) is a normal bundle valued tensor of type \((0, 3)\) and is called the third fundamental form of \(M\). Here, \(\nabla\) is called the van der Waerden–Bortolotti connection of \(M\). If \(\nabla h = 0\), then \(f\) is called parallel \([8]\). The second covariant derivative \(\nabla^2 h\) of \(h\) is
defined by
\[
(\nabla^2 h)(Z, W, X, Y) = (\nabla_X \nabla_Y h)(Z, W) \\
= \nabla^\perp_X((\nabla_Y h)(Z, W)) - (\nabla_Y h)(\nabla_X Z, W) \\
- (\nabla_X h)(Z, \nabla_Y W) - (\nabla_{\nabla_Y h})(Z, W).
\]  

Then we have
\[
(\nabla_X \nabla_Y h)(Z, W) - (\nabla_Y \nabla_X h)(Z, W) = (\tilde{R}(X, Y) \cdot h)(Z, W) \\
= R^\perp(X, Y) h(Z, W) - h(R(X, Y)Z, W) - h(Z, R(X, Y)W),
\]  

where \(\tilde{R}\) is the curvature tensor belonging to the connection \(\nabla\). The basic equations of Gauss and Ricci are
\[
R(X, Y, Z, W) = g(R(X, Y)Z, W) = \tilde{g}(\tilde{R}(X, Y)Z, W) \\
+ \tilde{g}(h(Y, Z), h(X, W)) - \tilde{g}(h(X, Z), h(Y, W)),
\]
\[
\tilde{g}(R^\perp(X, Y) \xi, \eta) = g([A_\xi, A_\eta]X, Y); \; \xi, \eta \in N(M),
\]
respectively, and \(N(M)\) denotes the normal bundle of \(M\). Here \(\tilde{R}\) and \(R^\perp\) denote the curvature operator of \(CP^n\) and the normal connection defined by
\[
\tilde{g}(\tilde{R}(X, Y)Z, W) = g(Y, Z)g(X, W) - g(X, Z)g(Y, W)
\]
and
\[
R^\perp(X, Y)Z = \nabla^\perp_X \nabla^\perp_Y Z - \nabla^\perp_Y \nabla^\perp_X Z - \nabla^\perp_{[X,Y]}Z,
\]
respectively. The \textit{Weyl conformal curvature tensor} of an \(n\)-dimensional Riemannian manifold \((M, g)\) is defined by
\[
C(X, Y, Z, W) = R(X, Y, Z, W) - \frac{1}{n-2} [S(Y, Z)g(X, W) \\
- S(X, Z)g(Y, W) + S(X, W)g(Y, Z) - S(Y, W)g(X, Z)] \\
+ \frac{1}{(n-1)(n-2)} (g(Y, Z)g(X, W) - g(X, Z)g(Y, W)).
\]
For \(n \geq 4\), if \(C = 0\), then \(M\) is called \textit{conformally flat} \[15\].

We choose local field of orthonormal frames \(\{e_1, e_2, \ldots, e_n, J e_1 = e_1, \ldots, J e_n = e_n\}\) in \(CP^n\) such that, restricted to \(M\), the vectors \(e_1, e_2, \ldots, e_n\) are tangent to \(M\). Then for \(1 \leq i, j \leq n\), the components of the second fundamental form \(h\) are given by
\[
h(e_i, e_j) = \sum h^k_{ij} e_k^* \]
and satisfy
\[
h^k_{ij} = h^k_{ji} = h^k_{kj}.
\]
Similarly, the components of the first and the second covariant derivative of $h$ are given by

$$h_{ij}^\alpha = g((\nabla_{e_i} h)(e_j), e_\alpha) = \nabla_{e_i} h_{ij}^\alpha$$

and

$$h_{ij}^\alpha = g((\nabla_{e_i} \nabla_{e_j} h)(e_i, e_j), e_\alpha) = \nabla_{e_i} \nabla_{e_j} h_{ij}^\alpha,$$

respectively.

Moreover, the components $R_{ijkh}$ of the curvature tensor $R$, the components $S_{ik} = \sum R_{ijkh}$ of the Ricci tensor $S$ and the scalar curvature $\tau = \sum S_{ij}$ are given by

$$R_{ijkh} = (\delta_{ik}\delta_{jh} - \delta_{ih}\delta_{jk}) + \sum (h_{ik}^\rho h_{jk}^\rho - h_{ih}^\rho h_{jk}^\rho),$$

$$S_{ik} = (n-1)\delta_{ik} + \sum (trA_r)g(A_r e_i, e_k) - \sum g(A_r e_i, A_r e_k)$$

and

$$\tau = n(n - 1) + \sum (trA_r)^2 - \|h\|^2,$$

respectively, where

$$\|h\|^2 = \sum tr(A_r^2) = \sum (h_{ik}^\rho)^2.$$

**Proof of Theorem 1.** It was proven in [3] that the second fundamental form of the immersion satisfies

$$\frac{1}{2} \Delta \|h\|^2 = \|\nabla h\|^2 + \sum tr(A_r A_r - A_r A_r)^2 - \sum tr(A_r A_r)^2 + (n + 1)\|h\|^2.$$  

(16)

Since

$$\sum tr(A_r A_r - A_r A_r)^2 = - \sum \left( \sum (h_{km}^\rho h_{lm}^\rho - h_{km}^\rho h_{lm}^\rho) \right)^2,$$

by the use of Gauss equation we have

$$\sum tr(A_r A_r - A_r A_r)^2 = \|R\|^2 + 4\tau - 2n(n - 1)$$

and

$$\sum tr(A_r A_r)^2 = \|S\|^2 - 2(n - 1)\tau + n(n - 1)^2,$$

(17)

(18)
In view of (17) and (18), equation (16) can be written as

$$
\frac{1}{2} \Delta \|h\|^2 = \|\nabla h\|^2 - \|R\|^2 - \|S\|^2 + (n + 1)\tau.
$$

Furthermore, it is known that (see [2])

$$
\|R\|^2 \geq \frac{4}{n - 2} \|S\|^2 - \frac{2\tau^2}{(n - 1)(n - 2)},
$$

equality holding if and only if $M$ is conformally flat.

Since $M$ is semi-parallel, then by definition the condition

$$
\overline{R}(e_l, e_k) \cdot h = 0
$$

is fulfilled for $1 \leq k, l \leq n$.

By (4), we have

$$
(\overline{R}(e_l, e_k) \cdot h)(e_i, e_j) = (\nabla_{e_i} \nabla_{e_j} h)(e_l, e_k) - (\nabla_{e_k} \nabla_{e_l} h)(e_i, e_j).
$$

By the use of (10) and (11) the semi-parallelity condition (21) turns into

$$
h_{ij}^{\alpha} g_{k\ell} = h_{\alpha}^{\ell} g_{ij},
$$

where $g(e_i, e_j) = \delta_{ij}$ and $1 \leq i, j, k, l \leq n$, $n + 1 \leq \alpha \leq 2n$.

Recall that the Laplacian $\Delta h_{ij}^{\alpha}$ of $h_{ij}^{\alpha}$ is defined by

$$
\Delta h_{ij}^{\alpha} = \sum_{i,j,k=1}^{n} h_{ij}^{\alpha} g_{k\ell},
$$

Then we obtain

$$
\frac{1}{2} \Delta (\|h\|^2) = \sum_{i,j,k=1}^{n} \sum_{\alpha=n+1}^{2n} h_{ij}^{\alpha} h_{k\ell}^{\alpha} + \|\nabla h\|^2,
$$

where

$$
\|h\|^2 = \sum_{i,j,k=1}^{n} \sum_{\alpha=n+1}^{2n} (h_{ij}^{\alpha})^2
$$

and

$$
\|\nabla h\|^2 = \sum_{i,j,k=1}^{n} \sum_{\alpha=n+1}^{2n} (h_{ij}^{\alpha} g_{k\ell})^2
$$
are the squares of the lengths of the second and third fundamental forms of $M$, respectively. In addition, using (8) and (11), we obtain

$$h''_{ij}h''_{ijkk} = g(h(e_i, e_j), e_a)g((\nabla_{e_k} \nabla_{e_k} h)(e_i, e_j), e_a)$$

$$= g((\nabla_{e_k} \nabla_{e_k} h)(e_i, e_j)g(h(e_i, e_j), e_a), e_a)$$

$$= g((\nabla_{e_k} \nabla_{e_k} h)(e_i, e_j), h(e_i, e_j)). \quad (28)$$

Therefore due to (28), equation (25) becomes

$$\frac{1}{2} \Delta(\|h\|^2) = \sum_{i,j,k=1}^{n} g((\nabla_{e_k} \nabla_{e_k} h)(e_i, e_j), h(e_i, e_j)) + \|\nabla h\|^2. \quad (29)$$

Furthermore by definition

$$\|h\|^2 = \sum_{i,j=1}^{n} g(h(e_i, e_j), h(e_i, e_j)),$$

$$H^\alpha = \sum_{k=1}^{n} h''_{kk}^\alpha,$$

$$\|H\|^2 = \frac{1}{h^2} \sum_{\alpha=n+1}^{2n} (H^\alpha)^2,$$

and using equations (23)–(25), we get

$$\frac{1}{2} \Delta(\|h\|^2) = \sum_{i,j,k=1}^{n} \sum_{\alpha=n+1}^{2n} h''_{ij}^\alpha(\nabla_{e_i} \nabla_{e_j} H^\alpha) + \|\nabla h\|^2. \quad (30)$$

Using minimality condition, equation (30) reduces to

$$\frac{1}{2} \Delta(\|h\|^2) = \|\nabla h\|^2. \quad (31)$$

So comparing equations (19) and (31) we obtain

$$\|R\|^2 + \|S\|^2 - (n + 1)\tau = 0, \quad (32)$$

which gives us, from (32) and (20),

$$\left(\frac{n + 2}{n - 2}\right) \|S\|^2 - \frac{2\tau^2}{(n - 1)(n - 2)} - (n + 1)\tau \leq 0. \quad (33)$$

Using (18), equation (33) turns into

$$\left(\frac{n + 2}{n - 2}\right) (2(n - 1)\tau - n(n - 1)^2 + \sum \text{tr}(A_{ij} A_{ij})^2)$$

$$- \frac{2\tau^2}{(n - 1)(n - 2)} - (n + 1)\tau \leq 0, \quad (34)$$
which gives us
\[
- \frac{2}{(n-1)(n-2)} \tau^2 + \frac{n^2 + 3n - 2}{n-2} \tau - \frac{n(n-1)^2(n+2)}{n-2} \leq 0.
\]

If \(\tau\) is between \(n(n-1)\) and \(\frac{n^3-3n+2}{2}\), then \(\tau = n(n-1)\) or \(\tau = \frac{n^3-3n+2}{2}\). If \(\tau = n(n-1)\), then using (14) we have
\[
n(n-1) = n(n-1) - \|h\|^2,
\]
which implies that \(M\) is totally geodesic. If \(\tau = \frac{n^3-3n+2}{2}\), then using (14), we have
\[
n^3 - 3n + 2 = n(n-1) - \|h\|^2.
\]
But this contradicts the fact that \(\|h\|^2 \geq 0\). Hence in view of Theorem C, \(M\) is an open part of real projective space \(\mathbb{RP}^n\). This completes proof of the theorem. \(\square\)

**Proof of Theorem 2.** From (33), since \(\|S\|^2 \geq 0\), we get
\[
\tau \left( \frac{2\tau}{(n-1)(n-2)} + (n+1) \right) \geq 0. \quad (35)
\]
If \(\tau\) is between \(-\frac{(n-1)(n-2)(n+1)}{2}\) and 0 we have \(\tau = \frac{-(n-1)(n-2)(n+1)}{2}\) or \(\tau = 0\). If \(\tau = \frac{-(n-1)(n-2)(n+1)}{2}\), then using (33) we get \(S = 0\). This contradicts \(\tau = \frac{-(n-1)(n-2)(n+1)}{2}\). If \(\tau = 0\), then using (32) we get \(R = 0\). Hence in view of Theorem C, \(M\) is an open part of the Clifford torus \(T^n \subset \mathbb{CP}^n\). So we get the result as required. \(\square\)

There are examples of semi-parallel minimal submanifolds of totally real submanifolds of \(\mathbb{CP}^n\) except \(\mathbb{RP}^n\) and \(T^n\). We give the following example:

**Example 2.1.** The submanifolds

(i) \(SU(p)/Z_p, n = p^2 - 1\),

(ii) \(SU(p)/SO(p)Z_p, n = (p - 1)(p + 2)/2\),

(iii) \(SU(2p)/Sp(p)Z_{2p}, n = (p - 1)(2p + 1)\), and

(iv) \(E_6/F_4Z_3, n = 26\),

are \(n\)-dimensional compact totally real minimal submanifolds embedded in \(\mathbb{CP}^n\) with parallel second fundamental forms [1]. It is well known that every submanifold with parallel second fundamental form is semi-parallel. So the submanifolds (i)–(iv) are semi-parallel.

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