COMPACT TOTALLY REAL SUBMANIFOLDS WITH PARALLEL MEAN CURVATURE VECTOR IN A COMPLEX SPACE FORM

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0. Introduction

A submanifold $M$ of a Kaehlerian manifold $\bar{M}$ is said to be totally real if each tangent space to $M$ is mapped to the normal space by the complex structure of $\bar{M}$. The concept was first introduced by Chen and Ogiue [2], who studied their fundamental properties. Many subjects for totally real submanifolds were investigated from various different points of view, as one of which Chen, Houh and Lue [1] and Yachida [8, 9] obtained investigating results of $m$-dimensional totally real submanifolds with parallel mean curvature vector in $2m$-dimensional complex space forms. Furthermore, Urbano [7] and Ohnita [5] recently determined also manifold structures of such a submanifold of positive curvature or of non-negative curvature, respectively.

The purpose of this paper is to investigate compact totally real submanifolds with parallel mean curvature vector of a complex space form.

Manifolds, submanifolds, geometric objects and mappings discussed in this paper are assumed to be differentiable and of $C^\infty$.

1. Totally real submanifolds of a Kaehlerian manifold

Let $(\bar{M}, \bar{g})$ be a Kaehlerian manifold of real dimension $2m$ equipped with an almost complex structure $J$ and a Hermitian metric $\bar{g}$. Let $\bar{M}$ be covered by a system of coordinate neighborhoods $\{ \bar{U}, y^A \}$, where here and in the sequel the following convention on the range of indices are used, unless otherwise stated:

$A, B, C, \ldots = 1, \ldots, n, n+1, \ldots, 2m,$

$h, i, j, \ldots = 1, \ldots, n,$

$u, v, w, \ldots = n+1, \ldots, 2m.$
The summation convention will be used with respect to those system of indices. We then have

\[(1.1) \quad J_A^B J_B^C = -\delta_A^C, \quad J_B^C J_A^D \tilde{g}_{CD} = \tilde{g}_{BA},\]

\(\delta_A^C\) being the Kronecker delta, \(J_B^A\), \(\tilde{g}_{BA}\) the components of \(J\) and \(\tilde{g}\), respectively. Denoting by \(\nabla_B\) the operator of covariant differentiation with respect to \(\tilde{g}_{AB}\), we get

\[(1.2) \quad \nabla_B J_C^A = 0.\]

Let \(M\) be an \(n\)-dimensional Riemannian manifold covered by a system of coordinate neighborhoods \(\{U; x^h\}\) and immersed isometrically in \(\overline{M}\) by the immersion \(\phi : M \longrightarrow \overline{M}\). When the argument is local, \(M\) need not be distinguished from \(\phi(M)\). We represent the immersion \(\phi\) locally by \(y^A = y^A(x^h)\) and put \(B_j^A = \partial_j y^A\), \((\partial_j = \partial / \partial x^i)\), then \(B_j = (B_j^A)\) are \(n\)-linearly independent local tangent vectors of \(M\). We choose \(2m-n\) mutually orthogonal unit normals \(C_z = (C_z^A)\) to \(M\). Then the induced Riemannian metric \(g_{ji}\) on \(M\) is given by

\[(1.3) \quad g_{ji} = \tilde{g}_{BC} B_j^B B_i^C.\]

Therefore, by denoting by \(\nabla_j\) the operator of van der Waerden –Bortolotti covariant differentiation with respect to \(g_{ji}\), the equations of Gauss and Weingarten for \(M\) are respectively obtained:

\[(1.4) \quad \nabla_j B_i^A = h_{ji}^x C_x^A, \quad \nabla_j C_x^A = -h_{ji}^x B_i^A,\]

where \(h_{ji}^x\) are the second fundamental forms in the direction of \(C_x\) and

\[(1.5) \quad h_{ji}^x = h_{ji}^x g_{ih} = h_{ji}^x g_{ih} g_{yx}, \quad g_{yx} = \tilde{g}_{BA} C_y^B C_x^A\]

being the metric tensor of the normal bundle and \((g^{ij}) = (g_{ji})^{-1}\).

An \(n\)-dimensional Riemannian manifold \(M\) immersed isometrically in \(\overline{M}\) is called a totally real submanifold of \(\overline{M}\) if \(J M_p \subset M_p^\perp\) for each point \(p\) of \(M\), where \(M_p\) denotes the tangent space of \(M\) at \(p\) and \(M_p^\perp\) the normal space to \(M\) at \(p\). In this case, \(JX\) is a normal vector to \(M\), provided that \(X\) is a tangent vector on \(M\). Thus it follows that the dimensions satisfy \(m \geq n\). Let \(N(M_p)\) be an orthogonal complement of \(J M_p\) in \(M_p^\perp\). Then the decomposition is obtained: \(M_p^\perp = J M_p \oplus N(M_p)\). Hence, it follows that the space \(N(M_p)\) is invariant under the action of \(J\). Accordingly we can put in each coordinate neighborhood of \(M\),

\[(1.6) \quad J_B^A B_j^B = J_j^x C_x^A,\]

\[(1.7) \quad J_B^A C_x^B = -J_x^i B_i^A + f_x^y C_y^A,\]
where we put \( J_{x} = \bar{g}(J_{B_{j}}, C_{x}) \), \( J_{xj} = -\bar{g}(J_{C_{z}}, B_{j}) \) and \( f_{xy} = \bar{g}(J_{C_{x}}, C_{y}). \) From these definitions we see that

\[
J_{x} + f_{yx} = 0, \quad J_{xj} = J_{xj}.
\]

By taking account of (1.1) and (1.3), it follows from (1.6) and (1.7) that

\[
\begin{align*}
J_{x}^{x} & = \delta_{x}^{y}, \quad J_{x}^{x} f_{x}^{y} = 0, \\
J_{x}^{x} f_{x}^{y} & = -\delta_{x}^{y} + J_{x}^{i} J_{j}^{y},
\end{align*}
\]

where \( J_{x}^{x} = J_{x}^{x}, f_{x}^{y} = f_{xx}^{x}, \) and \( g^{xx} \) is the contravariant component of \( g_{yx}. \) These show that \( f^{3} + f = 0. \) \( f \) being of constant rank, it defines the so-called \( f \)-structure in the normal bundle [10].

If we apply the operator \( \nabla_{j} \) of the covariant differentiation to (1.6) and (1.7) and make use of (1.1), (1.2), (1.4) and these equations, we get respectively

\[
\begin{align*}
h_{ii}^{x} J_{x}^{x} & = h_{j}^{x} J_{x}^{x}, \\
\nabla_{j} J_{x}^{x} & = h_{j}^{x} f_{x}^{y}, \\
\nabla_{j} f_{x}^{y} & = h_{jy}^{x} J_{i}^{y} - h_{j}^{x} J_{i}^{y}.
\end{align*}
\]

In the sequel, we assume that the ambient Kaehlerian Manifold \( \bar{M} \) is of constant holomorphic sectional curvature \( 4c \) and of real dimension \( 2m, \) which is called a complex space form and denoted by \( \bar{M}^{2m}(c). \) Then the curvature tensor \( \bar{R} \) of \( \bar{M}^{2m}(c) \) is given by

\[
\bar{R}_{DCA} = c(\bar{g}_{DA} \bar{g}_{CB} - \bar{g}_{CA} \bar{g}_{DB} + J_{DA} J_{CB} - J_{CA} J_{DB} - 2J_{DA} J_{DB}).
\]

Since the submanifold \( M \) is totally real, it follows from equations (1.6) \( \sim (1.9) \) that equations of Gauss, Codazzi and Ricci for \( M \) are respectively obtained:

\[
\begin{align*}
R_{kxh} & = c(g_{kk} g_{xi} - g_{jk} g_{hj}) + h_{hh}^{x} h_{jx} - h_{jx}^{x} h_{ki}, \\
\nabla_{h} h_{jx}^{x} - \nabla_{j} h_{kx}^{x} & = 0, \\
R_{jy} & = c(J_{jx} h_{iy} - J_{ix} h_{jy}) + h_{jr}^{x} h_{r}^{y} - h_{ir}^{x} h_{jy},
\end{align*}
\]

where \( R_{kxh} \) and \( R_{jy} \) are the Riemannian curvature tensor of \( M \) and that with respect to the connection induced in the normal bundle of \( M, \) respectively. We see from (1.13) that the Ricci tensor \( R_{ji} \) of \( M \) can be expressed as follows:

\[
R_{ji} = c(n - 1) g_{ji} + h_{x}^{x} h_{jx} - h_{jx}^{x} h_{r}^{r} - h_{r}^{x} h_{r}^{r}, \quad (h_{x} = g_{ji} h_{jx}).
\]

2. Parallel mean curvature vector

Let \( M \) be an \( n \)-dimensional totally real submanifold in a complex
space form $\overline{M}^{2n}(c)$ of constant holomorphic curvature $4c$. A normal vector field $\xi=(\xi^z)$ is called a parallel section in the normal bundle if it satisfies $\nabla_j\xi^z=0$, and furthermore a tensor field $F$ on $M$ is said to be parallel in the normal bundle if $\nabla_jF$ vanishes identically. In this section, the $f$-structure in the normal bundle is assumed to be parallel. In this case, the equation (1.12) is reduced to

$$h_{jz}F^z=h_{jz}J^z_j.$$  

Multiplying $h_{jz}J^z_j$ to (1.10) and summing up for $j$, $i$ and $h$ and making use of (2.1), we find

$$h_{jz}J^z_j=h_{jz}J^z_j,$$
which together with (1.9) gives

$$h_{jz}(\delta_y+f_zf_z^x)=h_{jz}h_{jz}.$$
Thus it follows that

$$h_{jz}f_z^x=0,$$  

for any index $x$, where we have used (1.11).

**Remark.** We notice from (1.9) that $f_z^x$ vanishes identically if $m=n$. Thus, an $n$-dimensional totally real submanifold of a real $2n$-dimensional Kaehlerian manifold has always a trivial $f$-structure in the normal bundle.

Applying $J^z_j$ to (1.10) and summing up for $h$, we obtain $h_{jz}=h_{jz}J^z_jJ^z_jJ^z_iJ^z_i$ with the aid of (1.9) and (2.2), from which we get, taking the skew-symmetric part of this with respect to indices $j$ and $i$,

$$(h_{jz}J^z_j)J^z_i=(h_{jz}J^z_j)J^z_i=0.$$  
Therefore we see, by a direct consequence of (1.9) and (2.2), that

$$h_{jz}J^z_j=P_{yz}^zJ^z_j,$$
where $P_{yz}^z$ is defined by $P_{yz}^z=h_{jz}J^z_jJ^z_iJ^z_i$ and hence it satisfies

$$P_{yz}^zf_z^w=0.$$  

Denoting $P_{yz}=g_{zw}P_{yz}^w$, we see that $P_{xyz}$ is symmetric with respect to all indices, because of (2.1). It follows from (2.3) that

$$h_{jz}P_{xyz}^w=J^z_jJ^z_iP_{xyz}^w,$$
which together with (1.9) and (2.3) gives $P_{xyz}P_{xyz}=h_{jz}h_{jz}$ and

$$h^z=P_z,$$
where $P_z=P_{yz}$.

From now on we denote the index $n+1$ by *. When $x=n+1$ in
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(2.4), we have

\[ h_{ji}^* = P_{ju}^* J_j^* J_i^*. \]

From this equation and (2.4) it is easily seen that

\[ h_{jr}^* h_{i}^* = P_{mu}^* P_{yu}^* J_j^* J_i^*. \]

Let \( \mathcal{J} \) be a mean curvature vector field of the submanifold. Namely, it is defined by

\[ \mathcal{J} = \frac{g_{ij} h_{ji}^* C_x}{n} = h^* C_x/n, \]

which is independent of the choice of the local field of orthonormal frames \( \{ C_x \} \). Since the fact that the mean curvature vector is parallel in the normal bundle is assumed, we may choose a local field \( \{ e_x \} \) in such a way that \( \mathcal{J} = a e_{n+1} \), where \( a = ||\mathcal{J}|| \) is constant. Because of the choice of the local field, the parallelism of \( \mathcal{J} \) yields

\[ h^* = na. \]

\( \mathcal{J} \) being a normal vector field on \( M \), the curvature tensor \( R_{jiyx} \) of the connection in the normal bundle shows that \( R_{jiyx} = 0 \) for any index \( x \). Thus the Ricci equation (1.15) gives

\[ h_{jr}^* h_{i}^* - h_{ir}^* h_{j}^* = c (J_j^* J_i^* - J_i^* J_j^*). \]

By the way, we notice from the first equation of (2.2) that

\[ f_{i}^* = 0, \]

because of the fact that \( \mathcal{J} \) is non trivial. For a normal vector field \( \xi \), let \( A_\xi \) be a shape operator of the tangent space \( M_p \) at \( p \) in the direction of \( \xi \), which is defined by \( g(A_\xi X, Y) = \bar{g}(\sigma(X, Y), \xi) \) for any tangent vectors \( X \) and \( Y \) of \( M_p \), where \( \sigma \) denotes the second fundamental form on the submanifold. In particular, the shape operator in the direction of \( C_{n+1} \) is denoted by \( A^* \). The following property is then obtained.

**Lemma 2.1.** Let \( M \) be a totally real submanifold with parallel \( f \)-structure in the normal bundle in a complex space form \( \overline{M}^{2m}(c) \). If the mean curvature vector is non trivial and parallel, and if \( A^* \) has no simple roots, then \( c = 0 \).

**Proof.** Since the shape operator \( A^* = (h_{ji}^*) \) is diagonalizable, a local field \( \{ e_i \} \) of orthonormal frames in \( M \) can be chosen in such a way that \( h_{ji}^* = \lambda_j \delta_{ji} \). Namely, \( \lambda_1, ..., \lambda_n \) are eigenvalues of \( A^* \). The equation (2.9) is then reduced to
We put \([i] = \{j : \lambda_i = \lambda_j\}\). For any integer \(i\) the assumption implies that there is an integer \(j\) in \([i]\) different from \(i\), and hence \(\lambda_i = \lambda_j\). It yields \(cJ_i^* = 0\), because of (1.9), and hence \(c = 0\) by means of (2.10). This concludes the proof.

**Remark.** Let \(M\) be an \(n\)-dimensional totally real submanifold in \(\overline{M}^{2n}(c)\) \((c \neq 0)\). It is shown that if the nontrivial mean curvature vector is parallel in the normal bundle, then the shape operator \(A^*\) has simple roots.

Now, the equation (2.9) together with (2.7) yields

\[
(P_{zu} u^* - P_{yu} z^* )J_j^* J_i^* = c(J_j^* J_i^* - J_i^* J_j^* )
\]

Hence it follows that

\[
(2.11) \quad P_{zu} u^* - P_{yu} z^* = c(\partial_{zu} J_i^* J_j^* - J_i^* J_j^* \partial_{yz})
\]

by means of (1.9), (2.3) and (2.10). Contracting \(x\) and \(y\) in (2.11) and making use of (1.9), (2.5) and (2.8), we find

\[
(2.12) \quad P_{zu} P_{xu} u^* - h^* P_{zu} = c(n-1) \partial_{zu},
\]

and hence

\[
(2.13) \quad P_{xz} u^* = h^* P_{zu} + c(n-1).
\]

By multiplying \(h^*\) to (2.11) and summing up for \(z\), it is easily seen that

\[
h^* P_{zu} u^* - h^* P_{yu} z^* = c(h^* J_i^* J_j^* - h^* \partial_{yz})
\]

by means of (2.3), (2.5), (2.8) and (2.10). From the fact that \(P_{xyz}\) is symmetric for all indices it follows that

\[
P_{uz} u^* P_{yz} u^* = P_{yz} u^* P_{uz} u^* + c(h^* - P_{zu} u^*)
\]

because \(f\) is non trivial, where we use (2.5) and (2.8).

Substituting (2.12) into the last equation and making use of (2.3), we obtain

\[
(2.14) \quad P_{uz} u^* P_{yz} u^* = h^* P_{zu} u^* + c(n-2) P_{zu} u^* + h^* u^*.
\]

**Lemma 2.2.** Let \(M\) be a totally real submanifold with parallel \(f\)-structure in the normal bundle in \(\overline{M}^{2n}(c)\). If the non trivial mean curvature vector is parallel, then

\[
(2.15) \quad \Delta(h_{ij}^* h_{ji}^*) = 2||\nabla h_{ij}^*||^2,
\]

where \(\Delta\) is the operator of Laplacian.
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**Proof.** The mean curvature vector being parallel in the normal bundle, the Laplacian of \( h_{ji}^* \) is given, using the Ricci formula for \( h_{ji}^* \), by

\[
\Delta h_{ji}^* = R_{ji} h_{ji}^* - R_{kji} h_{kk}^*.
\]

On the other hand, it follows from (1.16) and (2.8) that

\[
R_{ji} = c(n-1)g_{ji} + h^* h_{ji}^* - h_{ji} h_{ii}^*.
\]

If we substitute this and (1.13) into (2.16), we obtain

\[
\Delta h_{ji}^* = c n h_{ji}^* - c h^* g_{ji} + h^* h_{ij}^* h_{ii}^* - h_{kk}^* h_{kk}^* h_{jiy}
\]

\[
+ h^* h_{kk}^* h_{jhy} - h_{ij} h_{jhy} h_{ii}^*.
\]

By means of (2.10), it turns out to be

\[
\Delta h_{ji}^* = c n h_{ji}^* - c h^* g_{ji} + h^* h_{ij}^* h_{ii}^* - h_{kk}^* h_{kk}^* h_{jiy}
\]

\[
- c h^* (J_{ji}^* J_{ij}^* - J_{ji} J_{ij}^*).
\]

Thus it follows from (2.5), (2.6) and (2.8) that

\[
\Delta h_{ji}^* = c(n-1)h_{ji}^* - c h_{ji}^* (g_{ji} - J_{ji} J_{ij}^*)
\]

\[
+ h^* P_{xy}^* P_{xy}^* J_{ij}^* J_{ij}^* - P_{xy}^* P_{xy}^* h_{jiy}.
\]

Consequently it follows from the last equation that

\[
h_{ii}^* \Delta h_{ij}^* = c(n-1)P_{xy}^* P_{xy}^* - c h_{ij}^* + c h^* P_{xy}^*
\]

\[
+ h^* P_{xy}^* P_{xy}^* (P_{xy}^* P_{xy}^* - (P_{xy}^* P_{xy}^*) (P_{xy}^* P_{xy}^*))
\]

where we have used (1.9), (2.3), (2.6), (2.7) and (2.8). Substituting (2.12)~(2.14) into the above equation, we obtain \( h_{ij}^* \Delta h_{ij}^* = 0 \). This completes the proof.

**Corollary 2.3.** Let \( M \) be an \( m \)-dimensional totally real submanifold in \( \overline{M}^{2m}(c) \). If the nontrivial mean curvature is parallel, then (2.15) is valid.

### 3. Characterization of submanifolds

This section is devoted to investigating the manifold structure of compact totally real submanifolds in a complex space form \( \overline{M}^{2m}(c) \). Let \( M \) be an \( n \)-dimensional compact totally real submanifold of \( \overline{M}^{2m}(c) \) such that the \( f \)-structure in the normal bundle is parallel. If the non trivial mean curvature vector \( \mathcal{J} \) on \( M \) is parallel, then Lemma 2.2 says the second fundamental form \( h_{ji}^* \) in the direction of \( \mathcal{J} \) is parallel, that is, \( \nabla_{\mathcal{J}} h_{ji}^* = 0 \).
on $M$. When a function $h_m$ for any integer $m \geq 1$ is given by
$$h_m = h_{i_1}^{i_2} h_{i_3}^{i_4} \cdots h_{i_m}^{i_1},$$
it is easily seen that $h_m$ is constant on $M$ for any integer $m$, because $h_{ij}^{*}$ is parallel. This implies that each eigenvalue $\lambda_i$ of the shape operator $A^*$ is constant on $M$. By $\mu_1, \cdots, \mu_\alpha$ mutually distinct eigenvalues of $A^*$ are denoted. Let $n_1, \ldots, n_\alpha$ be their multiplicities. Since distinct eigenvalues $\mu_\alpha$ ($a=1, \ldots, \alpha$) is constant, the smooth distribution $T_\alpha$ which consists of all eigenspaces associated with the eigenvalue can be defined, and they are then mutually orthogonal. Furthermore, $A^*$ being parallel, these distributions $T_\alpha$ are parallel and hence completely integrable. Thus, by means of the de Rham decomposition theorem [3], the submanifold $M$ is a product of Riemannian manifolds $M_1 \times \cdots \times M_\alpha$, where the tangent bundle of $M_\alpha$ corresponds to $T_\alpha$. First of all, we shall prove

**Theorem 3.1.** Let $M$ be an $n$-dimensional compact totally real submanifold imbedded in a $2m$-dimensional complex Euclidean space $C_m$. If an $f$-structure in the normal bundle is parallel and if the mean curvature vector is parallel, then $M$ is a product submanifold $M_1 \times \cdots \times M_\alpha$, where $M_\alpha$ is a compact $n_\alpha$-dimensional totally real submanifold imbedded in $C_{m_\alpha}$ and $M_\alpha$ is contained in a hypersphere in $C_{ma}$.

Since the proof is accomplished by the quite same discussion as that in [1] and [6], it is only sketched. Since the ambient space is complex Euclidean, it can not admit compact minimal submanifolds. So, the mean curvature vector $\mathcal{J}$ is not trivial. Furthermore, since $\mathcal{J}$ is parallel in the normal bundle, each shape operator $A_\gamma$ satisfies $[A^*, A_\gamma]=0$, which implies $A_\gamma T_\alpha \subset T_\alpha$ for any indices $\gamma$ and $\alpha$. By means of Moore's Theorem [4], $M=M_1 \times \cdots \times M_\alpha$ is a product submanifold imbedded in $C_m=C_{m_1} \times \cdots \times C_{m_\alpha}$. Moreover, $M_\alpha$ is a totally real submanifold imbedded in some $C_{m_\alpha}^*$, because we can choose an orthonormal basis $e_1, \ldots, e_m$ for $JM^*_p$ and an orthonormal basis $e_{n+1}, \ldots, e_m, e_{n+1}, \ldots, e_{m*}$ for $N(M^*_p)$ in such a way that
$$h_{ij}^{k} = h_{jk}^{i} = h_{ki}^{j}, \quad h_{ij}^\lambda = 0 \quad \text{for} \quad \lambda = n+1, \ldots, m^*.$$Let $\pi_\alpha(\mathcal{J})$ be the component of $\mathcal{J}$ in the subspace $C_{m_\alpha}^*$. Then $\pi_\alpha(\mathcal{J})$ is a parallel mean curvature of $M_\alpha$ in $C_{m_\alpha}$, and $M_\alpha$ is umbilical with respect to $\pi_\alpha(\mathcal{J})$. Therefore it follows that $M_\alpha$ lies in a small hypersphere
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in $\mathbb{C}^m$ which is orthogonal to $\pi_a(\mathfrak{f})$, and hence it is a compact minimal submanifold in the hypersphere. This completes the proof.

As a direct consequence of Lemma 2.1 and Theorem 3.1, we have

**Theorem 3.2.** Let $M$ be an $n$-dimensional compact totally real submanifold with parallel $\mathfrak{f}$-structure in the normal bundle imbedded in a complex space form $\mathbb{C}^{2m}(c)$. If the non trivial mean curvature vector is parallel and if the shape operator $A^*$ has no simple roots, then $c=0$. In particular, if $\mathbb{C}^{2m}(c)=\mathbb{C}^m$, then $M$ is a product submanifold $M_1 \times \ldots \times M_a$.

**Theorem 3.3.** Let $M$ be an $n$-dimensional compact totally real submanifold with parallel $\mathfrak{f}$-structure in the normal bundle in a complex space form $\mathbb{C}^{2m}(c)$. If the non trivial mean curvature vector is parallel and if $M$ has no zero sectional curvature, then $c=0$. In particular, if $\mathbb{C}^{2m}(c)=\mathbb{C}^m$, then $M$ must be minimally contained in a hypersphere of positive curvature in $\mathbb{C}^m$.

**Theorem 3.4.** Let $M$ be a compact totally real submanifold with parallel $\mathfrak{f}$-structure in the normal bundle in a complex space form $\mathbb{C}^{2m}(c)$. If the non trivial mean curvature vector is parallel and if the shape operator $A^*$ has mutually distinct eigenvalues, then $M$ is flat and moreover the second fundamental form is parallel.

**Bibliography**

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