Abstract. We study nonlinear automorphisms of Levi degenerate hypersurfaces of finite multitype. By results of [23], the Lie algebra of infinitesimal CR automorphisms may contain a graded component consisting of nonlinear vector fields of arbitrarily high degree, which has no analog in the classical Levi nondegenerate case, or in the case of finite type hypersurfaces in $\mathbb{C}^2$. We analyze this phenomenon for hypersurfaces of finite Catlin multitype in complex dimension three. The results provide a complete classification of such manifolds. As a consequence, we show on which hypersurfaces 2-jets are not sufficient to determine an automorphism. The results also confirm a conjecture about the origin of nonlinear automorphisms of Levi degenerate hypersurfaces, formulated by the first author (AIM 2010).

1. Introduction

One of the central problems in CR geometry is the classification of real hypersurfaces in $\mathbb{C}^n$, up to biholomorphic equivalence. A complete solution of this problem should also lead to a complete understanding of automorphism groups of such manifolds.

When the hypersurface is Levi nondegenerate, the problem is well understood thanks to the classical work of Chern and Moser [11]. In particular, the infinitesimal CR automorphisms of such manifolds form a graded Lie algebra with at most 5 components. Moreover, by results of Kruzhilin and Loboda ([29]), if a strongly pseudoconvex hypersurface is not equivalent to the sphere, there are at most 3 graded components, and all infinitesimal automorphisms are linear in appropriate coordinates. For the sphere itself, the coefficients are at most quadratic, which implies 2-jet determination in general.

Similar results were obtained for hypersurfaces of finite type in $\mathbb{C}^2$. In particular, the same 2-jet determination result holds (see [16], [24]).

In a recent paper [23], the same problem is considered for Levi degenerate hypersurfaces in $\mathbb{C}^n$ with weighted homogeneous polynomial models, which replace the model hyperquadric from the nondegenerate case. The results describe possible structures of infinitesimal CR automorphism algebras for hypersurfaces of finite Catlin multitype. Compared to the Levi nondegenerate case, there are in general 6 possible components. The new phenomenon is the existence of nonlinear infinitesimal CR automorphisms in the complex tangential variables, which are of arbitrarily high degree in general.

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Our aim in this paper is to analyze this phenomenon and provide a complete description of hypersurfaces of finite Catlin multitype in $\mathbb{C}^3$ which admit such automorphisms.

Let us recall that the Catlin multitype is an important CR invariant which Catlin introduced to prove subelliptic estimates on pseudoconvex domains ([9], [10]). The definition of multitype was extended to the general case (not necessarily pseudoconvex) in [25]. It provides a natural setting for an extension of the Chern-Moser theory to degenerate manifolds ([23]).

We consider a weighted homogeneous model of finite Catlin multitype that is holomorphically nondegenerate. Let

\[(1.1) \quad M_P := \{ \text{Im } w = P(z, \bar{z}) \}, \quad (z, w) \in \mathbb{C}^2 \times \mathbb{C},\]

where $P$ is a real valued weighted homogeneous polynomial with respect to the multitype weights $\mu_1, \mu_2$ (see Section 2 for the needed definitions).

As proved in [23], the Lie algebra of infinitesimal CR automorphisms $\mathfrak{g} = \text{aut}(M_P, 0)$ of $M_P$ admits the weighted decomposition given by

\[(1.2) \quad \mathfrak{g} = \mathfrak{g}_{-1} \oplus \bigoplus_{j=1}^{2} \mathfrak{g}_{-\mu_j} \oplus \mathfrak{g}_0 \oplus \mathfrak{g}_c \oplus \mathfrak{g}_n \oplus \mathfrak{g}_1.\]

Here $\mathfrak{g}_c$ contains vector fields commuting with $W$ and $\mathfrak{g}_n$ contains vector fields not commuting with $W$, both of weight $\mu \in (0, 1)$ (see [23] for more details). Notice that $\mathfrak{g}_{-1}$ contains $W = \partial_w$ and $\mathfrak{g}_0$ contains the weighted Euler field, hence they are always non-trivial. A complete description of $\mathfrak{g}_1$ is also contained in [23].

Remark 1.1. By the results of [23], the elements of $\mathfrak{g}_n$ and $\mathfrak{g}_1$ are determined by ordinary 2-jets, hence higher order infinitesimal automorphisms may occur only when $\mathfrak{g}_c$ is nontrivial.

In this paper, we study all hypersurfaces whose model has nontrivial $\mathfrak{g}_c$. Our results confirm a conjecture about the origin of nonlinear automorphisms of Levi degenerate hypersurfaces formulated by the first author (see the 2010 AIM list of problems http://www.aimath.org/WWN/crmappings/crmappings.pdf): $M_P$ has a nonlinear symmetry if and only if there is a holomorphic mapping $f$ of $M_p$ into a hyperquadric in $\mathbb{C}^K$ and a symmetry of the hyperquadric, which is $f$-related to the automorphism of $M_P$.

Note that mappings of CR manifolds into hyperquadrics have been studied intensively in recent years (see e.g. [1], [14]). Here we ask in addition compatibility with a symmetry of the hyperquadric. Let us remark that analysing $\mathfrak{g}_n$ requires completely different techniques, and is the subject of a forthcoming paper [28].

In order to formulate our first result, let us recall that two vector fields $X_1$ and $X_2$ are $f$-related (or compatible by $f$) if $f_*(X_1) = X_2$.

**Theorem 1.2.** Let $M_P$ be a holomorphically nondegenerate hypersurface given by (1.1). Assume that $\dim \mathfrak{g}_c > 0$ and let $Y \in \mathfrak{g}_c$ be a nonzero vector field. Then there exist an integer $K \geq 3$ and a holomorphic polynomial mapping $f : \mathbb{C}^3 \to \mathbb{C}^K$ which maps $M_P$ into a hyperquadric $H \subseteq \mathbb{C}^K$, such that $Y$ is $f$-related with an infinitesimal CR automorphism of $H$. 
The proof is based on an explicit complete description of models with nontrivial \( g_c \), for which we need the following definition.

**Definition 1.3.** Let \( Y \) be a weighted homogeneous vector field. A pair of finite sequences of holomorphic weighted homogeneous polynomials \( \{ U^1, \ldots, U^n \} \) and \( \{ V^1, \ldots, V^n \} \) is called a symmetric pair of \( Y \)-chains if

\[
Y(U^n) = 0, \quad Y(U^j) = c_j U^{j+1}, \quad j = 1, \ldots, n - 1,
\]

\[
Y(V^n) = 0, \quad Y(V^j) = d_j V^{j+1}, \quad j = 1, \ldots, n - 1,
\]

where \( c_j, d_j \) are non zero complex constants, which satisfy

\[
c_j = -\bar{d}_{n-j}.
\]

If the two sequences are identical we say that \( \{ U^1, \ldots, U^n \} \) is a symmetric \( Y \)-chain.

**Example 1.4.** Let

\[
Y = iz^2 \left( \frac{\partial}{\partial z_1} \right).
\]

Then the pair \( \{ U^1, U^2 \} = \{ z_1, \bar{z}_1 \} \) is a symmetric \( Y \)-chain, since \( Y(U^2) = 0 \) and \( Y(U^1) = iU^2 \). Then for the hypersurface given by

\[
\text{Im} \ w = \text{Re} U^1 \overline{U^2} = \text{Re} z_1 \bar{z}_2
\]

we have \( Y \in g_c \).

The following result shows that in general the elements of \( g_c \) arise in an analogous way.

**Theorem 1.5.** Let \( M_P \) be given by (1.1) admitting a nontrivial \( Y \in g_c \). Then \( P \) can be decomposed in the following way

\[
P = \sum_{j=1}^{M} T_j,
\]

where each \( T_j \) is given by

\[
T_j = \text{Re} \left( \sum_{k=1}^{N_j} U^k \overline{V}^{N_j-k+1} \right),
\]

where \( \{ U^1, \ldots, U^{N_j} \} \) and \( \{ V^1, \ldots, V^{N_j} \} \) are a symmetric pair of \( Y \)-chains.

Conversely, if \( Y \) and \( P \) satisfy (1.3) - (1.7), then \( Y \in g_c \).

**Remark 1.6.** It is immediate to see that \( Y \) is uniquely and explicitly determined by \( P \). More precisely, since \( M_P \) is holomorphically nondegenerate, at least one of the \( T_j \) has length \( N_j \geq 2 \). For such a \( T_j \) we have

\[
Y = \frac{c_{N_j-1} U_j^{N_j-1}}{\Delta} \left( -\frac{\partial U_j^{N_j}}{\partial z_2} \frac{1}{\bar{z}_2} + \frac{\partial U_j^{N_j}}{\partial z_1} \frac{1}{\bar{z}_1} \right),
\]
where $\Delta$ is the Jacobian of $\{U_N^{N_j-1}, U_N^{N_j}\}$. Hence for a given hypersurface the results also provide a simple constructive tool to determine $\mathfrak{g}_c$. Moreover, this also shows that the real dimension of $\mathfrak{g}_c$ is at most one.

Examples of symmetric chains of arbitrary length are described at the end of Section 3. Using Remark 1.1 we obtain

**Theorem 1.7.** Let $M$ be an arbitrary smooth hypersurface of finite Catlin multitype. If its model is holomorphically nondegenerate and not biholomorphically equivalent to one of the form described in Theorem 1.3 then the automorphisms of $M$ are determined by their 2-jets.

The paper is organized as follows. Section 2 contains the necessary definitions used in the rest of the paper. Section 3 deals with the $\mathfrak{g}_c$ component of the algebra $\text{aut}(M_{P, 0})$. Section 4 completes the proofs of the above theorems.

## 2. Preliminaries

Let $M \subseteq \mathbb{C}^3$ be a smooth hypersurface, and $p \in M$ be a point of finite type $m \geq 2$ in the sense of Kohn and Bloom-Graham ([5], [6], [22]). We consider local holomorphic coordinates $(z, w)$ vanishing at $p$, where $z = (z_1, z_2)$ and $z_j = x_j + iy_j, j = 1, 2$, and $w = u + iv$. The hyperplane $\{v = 0\}$ is assumed to be tangent to $M$ at $p$, hence $M$ is described near $p = 0$ as the graph of a uniquely determined real valued function

\[ v = \varphi(z_1, z_2, \bar{z}_1, \bar{z}_2, u), \quad d\varphi(0) = 0. \]

We can assume that (see e.g. [5])

\[ \varphi(z_1, z_2, \bar{z}_1, \bar{z}_2, u) = P_m(z, \bar{z}) + o(u, |z|^m), \]

where $P_m(z, \bar{z})$ is a nonzero homogeneous polynomial of degree $m$ without pluriharmonic terms.

Recall that the definition of multitype involves rational weights associated to the variables $w, z_1, z_2$. The variables $w, u$ and $v$ are given weight one, reflecting our choice of tangential and normal variables. The complex tangential variables $(z_1, z_2)$ are treated according to the following definitions (for more details, see [25]).

**Definition 2.1.** A weight is a pair of nonnegative rational numbers $\Lambda = (\lambda_1, \lambda_2)$, where $0 \leq \lambda_j \leq \frac{1}{2}$, and $\lambda_1 \geq \lambda_2$.

Let $\Lambda = (\lambda_1, \lambda_2)$ be a weight, and $\alpha = (\alpha_1, \alpha_2), \beta = (\beta_1, \beta_2)$ be multiindices. The weighted degree $\kappa$ of a monomial

\[ q(z, \bar{z}, u) = c_{\alpha \beta} z^\alpha \bar{z}^\beta u^l, \quad l \in \mathbb{N}, \]

is defined as

\[ \kappa := l + \sum_{i=1}^{2} (\alpha_i + \beta_i) \lambda_i. \]
A polynomial $Q(z, \bar{z}, u)$ is weighted homogeneous of weighted degree $\kappa$ if it is a sum of monomials of weighted degree $\kappa$.

For a weight $\Lambda$, the weighted length of a multiindex $\alpha = (\alpha_1, \alpha_2)$ is defined by

$$|\alpha|_\Lambda := \lambda_1 \alpha_1 + \lambda_2 \alpha_2.$$

Similarly, if $\alpha = (\alpha_1, \alpha_2)$ and $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2)$ are two multiindices, the weighted length of the pair $(\alpha, \hat{\alpha})$ is

$$|(\alpha, \hat{\alpha})|_\Lambda := \lambda_1 (\alpha_1 + \hat{\alpha}_1) + \lambda_2 (\alpha_2 + \hat{\alpha}_2).$$

**Definition 2.2.** A weight $\Lambda$ will be called distinguished for $M$ if there exist local holomorphic coordinates $(z, w)$ in which the defining equation of $M$ takes form (2.3)

$$v = P(z, \bar{z}) + o_\Lambda(1),$$

where $P(z, \bar{z})$ is a nonzero $\Lambda$-homogeneous polynomial of weighted degree 1 without pluriharmonic terms, and $o_\Lambda(1)$ denotes a smooth function whose derivatives of weighted order less than or equal to one vanish.

The fact that distinguished weights do exist follows from (2.2). For these coordinates $(z, w)$, we have

$$\Lambda = \left( \frac{1}{m_1}, \frac{1}{m_2} \right).$$

In the following we shall consider the standard lexicographic order on the set of pairs. We recall the following definition (see [9]).

**Definition 2.3.** Let $\Lambda_M = (\mu_1, \mu_2)$ be the infimum of all possible distinguished weights $\Lambda$ with respect to the lexicographic order. The multitype of $M$ at $p$ is defined to be the pair

$$(m_1, m_2),$$

where

$$m_j = \begin{cases} \frac{1}{\mu_j} & \text{if } \mu_j \neq 0 \\ \infty & \text{if } \mu_j = 0. \end{cases}$$

If none of the $m_j$ is infinity, we say that $M$ is of finite multitype at $p$.

Clearly, since the definition of multitype includes all distinguished weights, the infimum is a biholomorphic invariant.

Coordinates corresponding to the multitype weight $\Lambda_M$, in which the local description of $M$ has form (2.3), with $P$ being $\Lambda_M$-homogeneous, are called multitype coordinates. If $M$ is of finite multitype at $p$, the infimum in (2.3) is attained, which implies that multitype coordinates do exist ([9], [25]).

**Definition 2.4.** Let $M$ be given by (2.3). We define a model hypersurface $M_P$ associated to $M$ at $p = 0$ by

$$(2.4) \quad M_P = \{ (z, w) \in \mathbb{C}^3 \mid v = P(z, \bar{z}) \}.$$
Next let us recall the following definitions.

**Definition 2.5.** Let $X$ be a holomorphic vector field of the form

\[ X = \sum_{j=1}^{2} f^j(z, w) \partial_{z_j} + g(z, w) \partial_w. \]

We say that $X$ is rigid if $f^1, f^2, g$ are all independent of the variable $w$.

Note that the rigid vector field $W$, of homogeneous weight $-1$, given by

\[ W = \partial_w \]

lies in $\text{aut}(M_P, 0)$. We will denote by $E$ the weighted homogeneous vector field of weight 0 defined by

\[ E = \sum_{j=1}^{2} \mu_j z_j \partial_{z_j} + w \partial_w, \]

i.e. the weighted Euler field. Note that by definition of $\mu_j$, $E$ is a non rigid vector field lying in $\text{aut}(M_P, 0)$.

We can divide homogeneous rigid vector fields into three types, and introduce the following terminology.

**Definition 2.6.** Let $X \in \text{aut}(M_P, 0)$ be a rigid weighted homogeneous vector field. $X$ is called

1. a shift if the weighted degree of $X$ is less than zero;
2. a rotation if the weighted degree of $X$ is equal to zero;
3. a generalized rotation if the weighted degree of $X$ is bigger than zero

Notice that $X \in \text{aut}(M_P, 0)$ is a generalized rotation if and only if it has positive weighted degree and commutes with $W$. In other words, generalized rotations are precisely the elements of $\mathfrak{g}_c$.

### 3. Generalized rotations

In this section we study nonlinear infinitesimal CR automorphisms of hypersurfaces of finite multitype and derive an explicit description of all models which admit a generalized rotation.

**Lemma 3.1.** Let $Y = f_1 \partial_{z_1} + f_2 \partial_{z_2}$ be a weighted homogeneous holomorphic vector field of weighted degree $> 0$. Then the space of weighted homogeneous polynomials in $z$ of a given weighted degree $\nu$ annihilated by $X$ has complex dimension at most one.

**Proof.** First we claim that $Y$ cannot be a multiple of the Euler field. Indeed, if $Y = hE$ with $h$ holomorphic and nonconstant, then $Y(P) = 0$ has no homogeneous solution, since $\text{Re}Y(P) = \text{Re}hP \neq 0$. Hence there exists a point $q$ such that $Y(q)$ is not a multiple of the Euler field. This point lies on a uniquely determined complex curve $z_1^{m_1} = cz_2^{m_2}$, and
Y is transverse to this curve in a neighbourhood of q. By homogeneity, on this curve \( P(z_1, z_2) \) is determined up to a multiplicative complex constant. Fixing this constant, by the uniqueness property for solutions of complex ODEs (19), the equation \( Y(P) = 0 \) determines \( P \) uniquely in a neighbourhood of q. Since \( P \) is a polynomial, if it exists, it is determined uniquely. Hence the space of solutions of \( Y(P) = 0 \) is at most one dimensional.

\[ \square \]

**Lemma 3.2.** Let \( V_n, \ n \in \mathbb{N}, \) be the space
\[ (3.1) \quad V_n = \{ X | Y^n(X) = 0 \}, \]
where \( X \) is a holomorphic polynomial of a given constant weighted length and \( Y \) is a weighted homogeneous holomorphic vector field. Then
\[ (3.2) \quad \dim V_n \leq n. \]
Moreover, when \( d_n = \dim V_n > 0, \) one can choose a basis for \( V_n \) of the form
\[ (3.3) \quad \{ F^n_s, \ s = 1, 2, \ldots, d_n \ | \ Y^{d_n}(F^n_{d_n}) = 0, Y^{d_n-1}(F^n_{d_n}) \neq 0, Y^{d_n-1}(F^n_s) = 0, s = 1, 2, \ldots, d_n - 1 \} \]

**Proof.** We prove the lemma by induction. The case \( n = 1 \) is a direct application of the previous Lemma. Suppose now that the lemma is true for \( n \) and prove it for \( n + 1. \) We have
\[ (3.4) \quad V_{n+1} = \{ X | Y^{n+1}(X) = 0 \} = \{ X | Y^n(Y(X)) = 0 \}. \]
By induction, we obtain that
\[ (3.5) \quad Y(X) \in \text{span}[F^n_s, \ Y^{d_n}(F^n_{d_n}) = 0, Y^{d_n-1}(F^n_{d_n}) \neq 0, Y^{d_n-1}(F^n_s) = 0, s = 1, \ldots, d_n - 1] \]
which implies that
\[ (3.6) \quad \dim V_{n+1} \leq n + 1. \]
After performing a linear combination of the solutions \( X \) of (3.5), we may satisfy (3.3). \( \square \)

**Theorem 3.3.** Let \( M_P \) be given by (1.1) admitting a generalized rotation \( Y. \) Then \( P \) can be decomposed in the following way
\[ (3.7) \quad P = \sum_{j=1}^{M} T_j, \]
where each \( T_j \) is given by
\[ (3.8) \quad T_j = \text{Re} \left( \sum_{k=1}^{N_j} U_j^k V_j^{N_j-k+1} \right), \]
where \( \{ U_j^1, \ldots, U_j^{N_j} \} \) and \( \{ V_j^1, \ldots, V_j^{N_j} \} \) are a symmetric pair of \( Y - \) chains.
Proof. Let

\[ P = \sum_{k=1}^{l} P_k, \]

where \( P_1 \neq 0, P_l \neq 0 \), be the bihomogeneous expansion of \( P \). Each \( P_j \) is weighted homogeneous with respect to \( z \) of weighted degree \( c_j \) where \( c_1 < c_2 < \cdots < c_l \).

We may write

\[ P_1 = \sum_{j=1}^{r} S_{j}^{c_1} \]

with \( r \) minimal. Note that \( c_1 + \hat{c}_1 = 1 \). We claim that \( r = 1 \). Since \( Y \) is a generalized rotation, we must have

\[ Y(\sum_{j=1}^{r} S_{j}^{c_1}) = \sum_{j=1}^{r} S_{j}^{c_1} Y(S_{j}^{\hat{c}_1}) = 0. \]

Since \( r \) is minimal, this implies that

\[ Y(S_{j}^{\hat{c}_1}) = 0 \]

for all \( j \). Using Lemma 3.2, we conclude that

\[ S_{j}^{\hat{c}_1} \in \mathbb{S}^{\hat{c}_1}_j \]

for all \( j \). We may then write \( P_1 \) as

\[ P_1 = Q_{1}^{c_1} \]

Hence, \( r = 1 \) and the claim is proved. We write now

\[ P_k = \sum_{j=1}^{r_k} S_{j}^{c_k} \]

with \( r_k \) minimal.

We claim that \( P_k \) can be rewritten as

\[ P_k = Q_{k}^{c_k} \]

so that there is a \( d_k \leq k \) such that

\[ Y^{d_k}(Q_{k}^{c_k}) = 0, \quad Y^{d_k-1}(Q_{k}^{c_k}) \neq 0, \quad Y^{d_k-1}(\hat{P}_k) = 0. \]

We prove the claim by induction. The case \( k = 1 \) has just been proved.

Suppose by induction that (3.16) holds for \( k \). Since \( Y \) is a generalized rotation, we have

\[ Y(Q_{k}^{c_k}) + Y(\hat{P}_k) + \sum_{j=1}^{r_{k+1}} S_{j}^{c_{k+1}} Y(S_{j}^{c_{k+1}}) = 0. \]
Applying $\nabla^d k$ to (3.18), we get
\begin{equation}
\sum_{j=1}^{r_k+1} S_j^{c_k+1} \nabla d_k+1 (S_j^{c_k+1}) = 0.
\end{equation}
Since $r_{k+1}$ is minimal,
\begin{equation}
\nabla d_k+1 (S_j^{c_k+1}) = 0
\end{equation}
for all $j$. Using Lemma 3.2, we obtain that $r_{k+1} \leq d_k + 1 \leq k + 1$. Using (3.3), we may then rewrite $P_{k+1}$ in the form given by (3.16). The claim is then proved.

Let $N_1 \leq l$ be minimal such that
\[ Y(Q_k^{c_k}) \neq 0, \quad k = 1, \ldots, N_1 - 1, \quad Y(Q_{N_1}^{c_k}) = 0. \]

We consider the following set $E_1$ given by
\begin{equation}
E_1 = \{Q_k^{c_k} Q_k^{c_k}, \quad k = 1, \ldots, N_1\}
\end{equation}
Note that this set is not empty since $Y(Q_k^{c_k}) = 0$.

We claim that the following holds for every element of $E_1$.

1. $d_k = k$, $k = 1, \ldots, N_1$.
2. $Y(Q_k^{c_k}) = a_k Q_k^{c_{k+1}}$,
3. $Y(Q_{k+1}^{c_{k+1}}) = b_k^{c_k} Y(Q_k^{c_k}) + R_k$, where $Y^{-1}(R_k) = 0$.

We show that $d_k = k$ using induction as above. Indeed, suppose that this is true for $k < N_1 - 1$ and show that it is also true for $k + 1$. Using the fact that $Y$ is a generalized rotation, we have as in (3.18)
\begin{equation}
Y(Q_k^{c_k}) Q_k^{c_k} + Y(\tilde{P}_k) + (Q_k^{c_{k+1}} Y(Q_k^{c_{k+1}}) + Y(\tilde{P}_{k+1}) = 0.
\end{equation}
Applying $Y^{-1}$ to (3.22), we obtain
\begin{equation}
Y(Q_k^{c_k}) Y^{-1}(Q_k^{c_k}) + (Q_k^{c_{k+1}} Y(Q_k^{c_{k+1}}) = 0.
\end{equation}
Hence, using (3.23), $d_{k+1} = k + 1$ by definition of $E_1$, and hence
\begin{equation}
Y(Q_k^{c_k}) = a_k Q_k^{c_{k+1}}.
\end{equation}
\begin{equation}
Y^{k}(Q_{k+1}^{c_{k+1}}) = b_{k+1} Y^{k-1}(Q_k^{c_k}),
\end{equation}
which implies
\begin{equation}
Y^{k-1}(Y(Q_{k+1}^{c_{k+1}} - b_{k+1} Q_k^{c_k})) = 0.
\end{equation}
and hence
\[(3.27)\]
\[Y(Q^\zeta_{k+1}) = b_{k+1}Q^\zeta_k + R_k,\]
where \(Y^{k-1}(R_k) = 0\). This achieves the proof of the claim. Using (3.27) and (3.10), we may then assume without loss of generality that \(R_k = 0\). We define the chains by putting
\[(3.28)\]
\[
\begin{align*}
U^k_1 &:= Q^\xi_k, \\
V^k_1 &:= Q^\zeta_{N_1-k+1},
\end{align*}
\]
It follows from the above properties of \(E_1\) that \(U^k_1\) and \(V^k_1\) form a chain. In other words, we may write
\[(3.29)\]
\[P = \text{Re} \left( \sum_{k=1}^{N_1} U^k_1 \overline{V^k_{N_1-k+1}} \right) + \hat{P}, \quad k = 1, \ldots, N_1,
\]
It follows from (3.23) that \(Y\) is a generalized rotation for \(\text{Im} w = \text{Re} \left( \sum_{k=1}^{N_1} U^k_1 \overline{V^k_{N_1-k+1}} \right)\).

It follows from (3.23) that \(a_k = -\overline{b}_{k+1}\), which means that the \(U\) and \(V\) are a pair of symmetric chains. Hence \(Y\) is a generalized rotation also for \(\hat{P}\). We can repeat the above argument for \(\hat{P}\) and in a finite number of steps we reach conclusion of the theorem.

Note that symmetric chains and pairs of chains of any length can arise.

**Example 3.4.** Let
\[Y = z_2^2 \partial_{z_1} - z_1 z_2 \partial_{z_2}.\]
Given three integers \(1 \leq l \leq m \leq n\) we first define
\[U^l = z_1^m z_2^l.\]
We can build a symmetric \(Y\)-chain by setting \(U^j = c_j z_1^{n-l+j} z_2^n\) for \(j = 1, \ldots, l - 1\) for suitable constants \(c_j\). Analogously, setting in addition
\[V^l = z_1^m z_2^m\]
we can get in the same way a pair of symmetric \(Y\)-chains of arbitrary length \(l\).

4. **Proofs of the main results**

In this section we complete the proofs of the results stated in the introduction. The first part of Theorem 1.5 has been already proved in Section 3 (as Theorem 3.3). The second, converse part of the statement is immediate to verify.

In order to prove Theorem 1.7, we combine Theorem 1.5 with Theorem 4.7 and Theorem 6.2 from [23]. They imply that on a smooth hypersurface of finite Catlin multitype 2-jets are always sufficient to determine an element from \(g_1\) and \(g_n\).
Proof of Theorem 1.2. In the notation of Theorem 3.3 we set
\begin{equation}
K = 2 \sum_{j=1}^{M} N_j + 1. \tag{4.1}
\end{equation}
We define a hyperquadric in \( \mathbb{C}^{K+1} \) by
\begin{equation}
\text{Im} \eta = \text{Re} \sum_{j=1}^{M} \sum_{k=1}^{N_j} \zeta_{j,k} \bar{\zeta}'_{j,N_j-k+1}, \tag{4.2}
\end{equation}
and consider the mapping \( \mathbb{C}^3 \to \mathbb{C}^{K+1} \) given by \( \eta = w \) and
\begin{equation}
\zeta_{j,k} = U_j^k(z_1, z_2). \tag{4.3}
\end{equation}
and
\begin{equation}
\zeta'_{j,k} = V_j^k(z_1, z_2). \tag{4.4}
\end{equation}
It is immediate to verify that the automorphism \( Y \) of \( M_\beta \) is \( f \)-related to the automorphism of this hyperquadric, defined by
\begin{equation}
Z = \sum_{j=1}^{M} \sum_{k=2}^{N_j} c_{k-1,j} \zeta_{j,k} \partial \zeta_{j,k-1} + d_{k-1,j} \zeta'_{j,k} \partial \zeta'_{j,k-1}. \tag{4.5}
\end{equation}
Indeed, the condition for \( f \)-related vector fields becomes exactly the chain condition (1.3)-(1.5).

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