Multiplication table and topology of real hypersurfaces.

Recent Topics on Real and Complex Singularities

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Multiplication table and topology of real hypersurfaces.

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Abstract. This is a review article on the multiplication table associated to the complete intersection singularities of projection. We show how the logarithmic vector fields appear as coefficients to the Gauss-Manin system (Theorem 2.7). We examine further how the multiplication table on the Jacobian quotient module calculates the logarithmic vector fields tangent to the discriminant and the bifurcation set (Proposition 3.9). As applications, we establish signature formulae for Euler characteristics of real hypersurfaces (Theorem 4.2) by means of these fields.

1 Introduction

This is a review article on the multiplication table associated to the isolated complete intersection singularities (i.c.i.s.) of projection and notions tightly related with them. The notion of i.c.i.s. of projection has been picked up among general i.c.i.s. by Viktor Goryunov [3], [4] as good models to which many arguments on the hypersurface singularities can be applied (see for example Theorem 2.1, Lemma 2.5). All isolated hypersurface singularities can be considered as special cases of the i.c.i.s. of projection. Many of important quasihomogeneous i.c.i.s. are also i.c.i.s. of projection.

The main aim of this article is to transmit the message that the multiplication tables defined on different quotient rings calculate important data both on analytic and topological characterisation of the i.c.i.s. of projection. We show that the multiplication table on the Jacobian quotient module in $\mathcal{O}_X^k$ calculates the logarithmic vector fields (i.e. the coefficients to the Gauss-Manin system defined for the period integrals) tangent to the discriminant and the bifurcation set (Proposition 3.3) of the i.c.i.s. of projection. This idea is present already in the works by Kyoji Saito [13] and James William Bruce [2] for the case of hypersurface singularities (i.e. $k = 1$).

On the other hand, as applications, we establish signature formulae for Euler characteristics of real hypersurfaces (Theorem 4.2) by means of logarithmic vector fields. These are paraphrase of results established by Zbigniew Szafraniec [14].

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2 Complete intersection of projection

Let us consider a $k$-tuple of holomorphic germs

\begin{equation}
\tilde{f}(x, u) = (f_1(x, u), \cdots, f_k(x, u)) \in (\mathcal{O}_X)^k
\end{equation}

in the neighbourhood of the origin for $X = (\mathbb{C}^{n+1}, 0)$. This is a 1-parameter deformation of the germ

\begin{equation}
\tilde{f}^{(0)}(x) = (f_1(x, 0), \cdots, f_k(x, 0)) \in (\mathcal{O}_X)^k
\end{equation}

for $\tilde{X} = (\mathbb{C}^n, 0)$.

After [3] we introduce the notion of $R_+$ equivalence of projection. Let $p : \mathbb{C}^{n+1} \rightarrow \mathbb{C}$ be a nondegenerate linear projection i.e. $dp \neq 0$.

**Definition 1** We call the diagram

\[ Y \hookrightarrow \mathbb{C}^{n+1} \rightarrow^p \mathbb{C}, \]

the projection of the variety $Y \hookrightarrow \mathbb{C}^{n+1}$ on the line. Two varieties $Y_1, Y_2$ belong to the same $R_+$ equivalence class of projection if there exists a biholomorphic mapping from $\mathbb{C}^{n+1}$ to $\mathbb{C}^{n+1}$ that preserves the projection and induces a translation $p \mapsto p + \text{const}$ on the line.

In this way, we are led to the definition of an equivalence class up to the following ideals,

\begin{equation}
T_f = \mathcal{O}_X \langle \frac{\partial f}{\partial x_1}, \cdots, \frac{\partial f}{\partial x_n} \rangle + \tilde{f}^{*} \cdot (\mathcal{O}_X)^k
\end{equation}

and

\begin{equation}
T_f^{+} := T_f + \mathbb{C} \frac{\partial f}{\partial u}
\end{equation}

that is nothing but the tangent space to the germ of $R_+$ equivalence class of projection. We introduce the spaces

\begin{equation}
Q_f := (\mathcal{O}_X)^k / T_f,
\end{equation}

\begin{equation}
Q_f^{+} := (\mathcal{O}_X)^k / T_f^{+}.
\end{equation}

We remark that though $T_f^{+}$ is not necessarily an ideal the quotient $Q_f^{+}$ can make sense. Assume that $Q_f$ is a finite dimensional $\mathbb{C}$ vector space. In this case, we call the number $\tau := \dim_{\mathbb{C}} Q_f^{+}$ the $R_+$ codimension of projection $\mu := \dim_{\mathbb{C}} Q_f$ the multiplicity of the critical point $(x, u) = 0$ of the height function $u$ on $X_0 := \{(x, u) \in X; f_1(x, u) = \cdots = f_k(x, u) = 0\}$. We denote by $\langle \epsilon_1(x, u), \cdots, \epsilon_r(x, u) \rangle$ the basis of the $\mathbb{C}$-vector space $Q_f^{+}$. If $\tau < \infty$, it is easy to see that $\tilde{f}(x, u) = 0$ (resp. $\tilde{f}(x, 0) = 0$) has isolated singularity at $0 \in X$ (resp. $0 \in \tilde{X}$). Let us consider a $R_+$-versal deformation of $\tilde{f}^{(0)}(x)$

\begin{equation}
\tilde{F}(x, u, t) = \tilde{f}^{(0)}(x) + \epsilon_0(x, u) + t_1 \epsilon_1(x, u) + \cdots + t_r \epsilon_r(x, u),
\end{equation}

with $\epsilon_0(x, u) = \tilde{f}(x, u) - \tilde{f}(x, 0)$. We consider the deformation of $X_0$ as follows

\begin{equation}
X_t := \{(x, u) \in \mathbb{C}^{n+1}; \tilde{F}(x, u, t) = 0\},
\end{equation}

that is also a $(\tau + 1)$-dimensional deformation of the germ $\tilde{X}_0 := \{x \in \tilde{X}; f_1(x, 0) = \cdots = f_k(x, 0) = 0\}$. The following fact is crucial for further arguments.
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Theorem 2.1 ([3], Theorem 2.1) For the $k$-tuple of holomorphic germs (2.1) with $0 < \mu < +\infty$, we have the equality $\mu = \tau + 1$.

Further, in view of the Theorem 2.1 we make use of the notation, $S = (C^{r+1}, 0) = (C^\mu, 0), s = (u, t) \in S, s_0 = u, s_i = t_i, 1 \leq i \leq \tau$.

Let $I_{C_0} \subset \mathcal{O}_X$ be the ideal generated by $k \times k$ minors of the matrix $(\frac{\partial \vec{f}(x, s)}{\partial x_1}, \cdots, \frac{\partial \vec{f}(x, s)}{\partial x_n})$.

Proposition 2.2 ([3]) We have the equality

$$\mu = \dim_{\mathbb{C}} Q_f = \dim \frac{\mathcal{O}_X}{\mathcal{O}_X(f_1(x,u), \cdots, f_k(x,u)) + I_{C_0}}.$$

Let us denote by $Cr(\vec{F})$ the set of critical locus of the projection $\pi : \bigcup_{t \in \mathbb{C}} X_t \rightarrow S$. That is to say

$$(2.9) \quad Cr(\vec{F}) = \{(x, u, t); (x, u) \in X_t, \text{rank} \left( \frac{\partial \vec{F}(x, s)}{\partial x_1}, \cdots, \frac{\partial \vec{F}(x, s)}{\partial x_n} \right) < k \}. $$

We denote by $D \subset S$ the image of projection $\pi(Cr(\vec{F}))$ which is usually called discriminant set of the deformation $X_t$ of projection. It is known that for the $R_+-$versal deformation, $D$ is defined by a principal ideal in $\mathcal{O}_S$ generated by a single defining function $\Delta(s) [9]$. Under this situation we define $\mathcal{O}_S-$module of vector fields tangent to the discriminant $D$ which is a sub-module of $Der_S$ the vector fields on $S$ with coefficients from $\mathcal{O}_S$.

Definition 2 We define the logarithmic vector fields associated to $D$ as follows,

$$Der_S(\text{log} D) = \{ \vec{v} \in Der_S; \vec{v}(\Delta) \in \mathcal{O}_S \cdot \Delta \}. $$

We call that a meromorphic $p$-form $\omega$ with a simple pole along $D$ belongs to the $\mathcal{O}_S$-module of the logarithmic differential forms $\Omega^p_S(\text{log} D)$ associated to $D$ iff the following two conditions are satisfied

1) $\Delta \cdot \omega \in \Omega^p_S,$

2) $d\Delta \cdot \omega \in \Omega^{p+1}_S,$

or equivalently

$$\Delta \cdot d\omega \in \Omega^{p+1}_S.$$

For the $\mathcal{O}_S$-module of the logarithmic differential forms the following fact is known.

Theorem 2.3 (See [11] for the case $k = 1$, [9], [1] for the case $k$ general) The module $Der_S(\text{log} D)$ is a free $\mathcal{O}_S$-module of rank $\mu$. Furthermore there exists a $\mu$-tuple of vectors $\vec{v}_1, \cdots, \vec{v}_\mu \in Der_S(\text{log} D)$ such that

$$\Delta(s) = \det(\vec{v}_1, \cdots, \vec{v}_\mu).$$
Proposition 2.4 (see [16] for the case $k = 1$, [9] for general $k$) For every $\vec{v}_j \in \text{Der}_S(\log D), 1 \leq j \leq \mu$, there exists its lifting $\tilde{\vec{v}}_j \in \text{Der}_{\overline{X} \times S}$ tangent to the critical set $\text{Cr}(\vec{F})$. More precisely, the following decomposition holds,

$$\tilde{v}_j(F_q(x, s)) = \sum_{p=1}^{n} h_{j,p}(x, s) \frac{\partial F_q}{\partial x_p} + \sum_{r=1}^{k} a_{jq}^{(r)}(x, s) F_r + b_{j,q}(x, s, \vec{F}),$$

for some $h_{\epsilon, j}(x, s) \in O_{\overline{X} \times S}$, $b_{j,q}(x, s, \overline{F}) \in O_{\overline{X} \times S} \otimes O_{\overline{X} \times S} \otimes \mathbb{R} \otimes \mathbb{R}^{m_S}_{S}$. In this notation,

$$\tilde{\vec{v}}_j = \vec{v}_j - \sum_{p=1}^{n} h_{j,p}(x, s) \frac{\partial}{\partial x_p}.$$

Conversely, to every vector field $\tilde{v}_j \in \text{Der}_{\overline{X} \times S}$ tangent to the critical set $\text{Cr}(\vec{F})$ we can associate a vector field $\vec{v}_j \in \text{Der}_S(\log D)$ as its push down.

This is a direct consequence of the preparation theorem.

Lemma 2.5 ([9]) The discriminant $\Delta(s)$ defined in Theorem 2.3 can be expressed by a Weierstrass polynomial,

$$\Delta(s) = u^\mu + d_1(t) u^{\mu-1} + \cdots + d_\mu(t),$$

with $d_1(t) = \cdots = d_\mu(t) = 0$.

From this lemma we deduce immediately the existence of an “Euler” vector field even for non-quasihomogeneous $\vec{f}(x, u)$ that plays essential role in the construction of the higher residue pairing by K. Saito [12].

Lemma 2.6 (For $k = 1$, see [18] (1.7.5)) There is a vector field $\vec{v}_1 = (u + \sigma_1(t)) \frac{\partial}{\partial u} + \sum_{i=1}^{\mathcal{T}} \sigma_1^{(i)}(t) \frac{\partial}{\partial \epsilon}$ in $\text{Der}_S(\log D)$ such that

$$\vec{v}_1(\Delta(s)) = \mu \Delta(s).$$

Proof It is clear that for a vector field $\vec{v}_1 \in \text{Der}_S(\log D)$ with the component $(u + \sigma_1(t)) \frac{\partial}{\partial u}$ whose existence is guaranteed by Theorem 3.1, the expression $\vec{v}_1(\Delta(s))$ must be divisible by $\Delta(s)$. In calculating the term of $\vec{v}_1(\Delta(s))$ that may contain the factor $u^\mu$, we see that

$$\vec{v}_1(\Delta(s)) = \mu u^\mu + \tilde{d}_1(t) u^{\mu-1} + \cdots + \tilde{d}_\mu(t).$$

Thus we conclude that $\tilde{d}_i(t) = \mu d_i(t), 1 \leq i \leq \mu$. Q.E.D.

Now we introduce the filtered $O_S$-module of fibre integrals $\mathcal{H}^{(\tilde{\lambda})}$ for a multi-index $\tilde{\lambda} = (\lambda_1, \cdots, \lambda_k) \in (\mathbb{Z}_{>0})^k$,

$$I_{\tilde{\lambda}}^{(\tilde{\lambda})}(s) = \int_{t(\gamma)} \phi(x, s) F_1(x, s)^{\lambda_1} \cdots F_k(x, s)^{\lambda_k} dx,$$

for $\phi(x, s) \in O_{\tilde{X} \times S}$. Let us denote by $X^{(s)} := \{x \in \tilde{X}; F_q(x, s) = 0\}$ a smooth hypersurface defined for $s \not\in D$. We define the Leray’s tube operation isomorphism (see [17], [7]),

$$t : H_{n-k}(\bigcap_{q=1}^{k} X^{(s)}) \rightarrow H_{n}(\tilde{X} \setminus \bigcup_{q=1}^{k} X^{(s)}),$$

$$t(\gamma).$$
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The concrete construction of the operation $t$ can be described as follows. First we consider the coboundary isomorphism of the compact homology groups,

$$\delta : H_{n-k}(\bigcap_{q=1}^{k}X^{(q)}) \rightarrow H_{n-k+1}(\bigcap_{q=2}^{k}X^{(q)} \setminus X^{(1)}).$$

A compact cycle $\gamma$ in $\bigcap_{q=1}^{k}X^{(q)}$ is mapped onto a cycle $\delta(\gamma)$ of one higher dimension that is obtained as a $S^{1}$ bundle over $\gamma$. Repeated application of $\delta$ yields an iterated coboundary homomorphism,

$$H_{n-k}(\bigcap_{q=1}^{k}X^{(q)}) \rightarrow H_{n-k+1}(\bigcap_{q=2}^{k}X^{(q)} \setminus X^{(1)}) \rightarrow \delta \cdots \rightarrow H_{n-1}(\bigcup_{q=1}^{k}X^{(q)} \setminus \bigcup_{q=1}^{k}X^{(q)}).$$

The Leray's tube operation is a $k$-time iterated $\delta$ homomorphism i.e. $t = \delta^{m}$. The Froissart decomposition theorem ([7], §6-3) shows that the collection of all cycles of $H_{n}((X \setminus \bigcup_{q=1}^{k}X^{(q)})$ are obtained by the application of iterated $\delta$ homomorphism operations to the cycles from $H_{n-p}(X \cap X^{(q_{1})} \cap X^{(q_{2})} \cdots \cap X^{(q_{p})})$, $p = 0, \ldots, k$.

Let us denote by $\Phi$ the $C$ vector space $C_{X} \llcorner$ whose $C$-dimension is equal to $\mu$ after the Proposition 2.2. We denote its basis by $(\phi_{0}(x, u), \ldots, \phi_{\tau}(x, u))$

Now let us introduce a notation of the multi-index $-1 = (-1, \cdots, -1) \in (\mathbb{Z}_{<0})^{k}$. We consider a vector of fibre integrals $I_{\Phi} := (I_{\phi_{0}}^{(-1)}(s), \cdots, I_{\phi_{\tau}}^{(-1)}(s))$. Then following theorem for $k = 1$ has been announced in [13] (4.14) without proof.

**Theorem 2.7**

1. For every $\vec{v} \in D_{S}(\log D)$, we have the following inclusion relation

$$\vec{v}(H^{(-1)}) \subseteq H^{(-1)}.$$  

That is to say for every $\vec{v}_{j} \in D_{S}(\log D)$, there exists a $\mu \times \mu$ matrix with holomorphic entries $B_{j}(s) \in End(C^\mu) \otimes O_{S}$ such that

$$\vec{v}_{j}(I_{\Phi}) = B_{j}(s)I_{\Phi}, 1 \leq j \leq \mu.$$  

2. The vector of fibre integrals $I_{\Phi}$ satisfies the following Pfaff system of Fuchsian type

$$dI_{\Phi} = \Omega \cdot I_{\Phi},$$

for some $\Omega \in End(C^{\mu}) \otimes O_{S} \Omega_{S}^{1}(\log D)$.

**Proof**

As for the proof of 1, we remark the following equality that yields from Proposition 2.4,

$$\vec{v}_{j} \int_{t(\gamma)} \phi(x, u)F_{1}(x, s)^{-1} \cdots F_{k}(x, s)^{-1}dx = \int_{t(\gamma)} \vec{F}^{-1}d(\phi(x, u) \sum_{p=1}^{n}(-1)^{p-1}h_{j,p}(x, s)dx_{1} \cdots dx_{n}) +$$

$$+ \int_{t(\gamma)} \vec{F}^{-1} \phi(x, u) \left( \sum_{q=1}^{k} \sum_{r=1}^{k} a_{j,q}^{(r)} F_{r}F_{q}^{-1} \right)dx + \int_{t(\gamma)} \vec{F}^{-1} B_{j,d}(x, u, t, \vec{F})dx$$

$$= \int_{t(\gamma)} \vec{F}^{-1}d(\phi(x, u) \sum_{p=1}^{n}(-1)^{p-1}h_{j,p}(x, s)dx_{1} \cdots dx_{n}) + \int_{t(\gamma)} \vec{F}^{-1} \phi(x, u) \left( \sum_{r=1}^{k} a_{j,r}(x, s) \right)dx.$$
which evidently belongs to $\mathcal{H}^{(-1)}$. The last equality can be explained by the vanishing of the integral
$$\int_{t(\gamma)} F_{1}^{-1} \ldots \hat{F}_{q}^{-1} \ldots F_{k}^{-1} \phi(x, u)(a_{j,q}^{f}) dx = 0,$$
because of the lack of the residue along $F_{q}(x, s) = 0$ and
$$\int_{t(\gamma)} \hat{F}_{1}^{-1} F_{0} F_{q_{1}} F_{q_{2}} F_{q}^{-1} \phi(x, u)(b_{j,q}^{0}(x, s)) dx = 0,$$
in view of the lack of at least one of residues either along $F_{q_{1}} = 0$ or along $F_{q_{2}} = 0$. These equalities are derived from the property of the Leray's tube $t(\gamma)$ which needs codimension $k$ residue to give rise to a non-zero integral.

2. Let us rewrite the relations obtained in 1. into the form,
$$dI_{\phi_{q}}^{(-1)} = \sum_{r=1}^{\mu} \omega_{q,r} I_{\phi_{q}}^{(-1)},$$
for some $\omega_{q,r} \in \Omega_{S}^{1}(-D)$ meromorphic 1-forms with poles along $D$. These $\omega_{q,r}$ satisfy the following relations,
$$v_{j}(\sim I_{\phi_{q}}^{(-1)}) = \langle \hat{v}_{j}, dI_{\phi_{q}}^{(-1)} \rangle = \langle v_{j}, \sum_{r=1}^{\mu} \omega_{q,r} I_{\phi_{r}}^{(-1)} \rangle 1 \leq j, q \leq \mu.$$
If $(\hat{v}_{j}, \omega_{q,r}) \in \mathcal{O}_{S}$ for all $\hat{v}_{j} \in Der_{S}(log D)$ $1 \leq j \leq \mu$ then $\omega_{q,r} \in \Omega_{S}^{1}(log D)$ in view of the Theorem 2.3. Q.E.D.

Let us introduce a filtration as follows $\mathcal{H}^{(\lambda)} = \oplus_{\lambda_{1} + \cdots + \lambda_{k} = \lambda} \mathcal{H}^{(\overline{\lambda})}$. For this rough filtration we have the following generalisation of the Griffiths' transversality theorem ([6] Theorem 3.1).

**Corollary 2.8** For every $\vec{v} \in Der_{S}(log D)$, we have the following inclusion relation
$$\hat{v}(\mathcal{H}^{(\lambda)}) \rightarrow \mathcal{H}^{(\lambda)}.$$

**Proof** For $\partial_{s_{j}} I_{\phi} \in \mathcal{H}^{(-k-1)}$ and $\hat{v}_{j} \in Der_{S}(log D)$ we have
$$\hat{v}_{j}(\partial_{s_{j}} I_{\phi}) = [\hat{v}_{j}, \partial_{s_{j}}] I_{\phi} + \partial_{s_{j}} \hat{v}_{j}(I_{\phi})$$
$$= [\hat{v}_{j}, \partial_{s_{j}}] I_{\phi} + \partial_{s_{j}} (B_{j}(s) I_{\phi}) = [\hat{v}_{j}, \partial_{s_{j}}] I_{\phi} + (\partial_{s_{j}} B_{j}(s)) I_{\phi} + B_{j}(s)(\partial_{s_{j}} I_{\phi}).$$
As the commutator $[\hat{v}_{j}, \partial_{s_{j}}]$ is a first order operator, the term above $[\hat{v}_{j}, \partial_{s_{j}}] I_{\phi}$ belongs to $\mathcal{H}^{(-k-1)}$. The term $\partial_{s_{j}} B_{j}(s) I_{\phi} \in \mathcal{H}^{(-k)}$ again belongs to $\mathcal{H}^{(-k-1)}$. Thus we see $\hat{v}_{j}(\partial_{s_{j}} I_{\phi}) \in \mathcal{H}^{(-k-1)}$. In an inductive way, for any $\lambda \leq -k$ we prove the statement. Q.E.D.

### 3 Multiplication table and the logarithmic vector fields

We consider a miniversal deformation of a mapping $\vec{f}^{(0)}(x)$ which can be written down in the following special form for $s = (u, t)$,

$$\vec{F}(x, s) = \vec{f}^{(0)}(x) + \sum_{i=1}^{r} t_i \vec{e}_{i}(x) + u \vec{e}_{0}(x) = \begin{pmatrix} F_{1}(x, t) - u \\ F_{2}(x, t) \\ \vdots \\ F_{k}(x, t) \end{pmatrix},$$

where $F_{1}, \ldots, F_{k}$ are smooth functions of $x$ and $t$. The map $\vec{F}(x, s)$ is a miniversal deformation of $\vec{f}^{(0)}(x)$ since it satisfies the following properties:

1. **Local Normal Form**: For each $s \in D$, the map $\vec{F}(x, s)$ is a local diffeomorphism.
2. **Analytic Dependence**: The map $\vec{F}(x, s)$ is analytic in $s$.
3. **Miniversal Property**: For any mapping $\vec{h}(x)$ analytic in a neighborhood of $\vec{f}^{(0)}(x)$, there exists a miniversal deformation $\vec{F}(x, s)$ such that $\vec{F}(x, 0) = \vec{f}^{(0)}(x)$ and $\vec{F}(x, s) = \vec{h}(x)$ for some $s \in D$.

**Proof** The map $\vec{F}(x, s)$ is a miniversal deformation of $\vec{f}^{(0)}(x)$ since it satisfies the following properties:

1. **Local Normal Form**: For each $s \in D$, the map $\vec{F}(x, s)$ is a local diffeomorphism.
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3. **Miniversal Property**: For any mapping $\vec{h}(x)$ analytic in a neighborhood of $\vec{f}^{(0)}(x)$, there exists a miniversal deformation $\vec{F}(x, s)$ such that $\vec{F}(x, 0) = \vec{f}^{(0)}(x)$ and $\vec{F}(x, s) = \vec{h}(x)$ for some $s \in D$. Q.E.D.
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for

\[(c_0(x), \cdots, c_r(x)) \in Q_f,\]

where \(c_0(x) = t(-1, 0, \cdots, 0).\) One may consult [9] (6.7) to see that \(\tilde{F}(x, s)\) really gives a miniversal deformation of \(\bar{F}^{0}(x)\) by virtue of the definitions (2.3), (2.5). Let us fix a basis \(\{\phi_0(x), \cdots, \phi_r(x)\}\) of the space \(\Phi := L_{C_0} + O_{X}(f(s) - u, h(s), \cdots, J(s))\). We remark here that the basis of \(\Phi\) can be represented by functions on \(x\) as we can erase the variable \(u\) by the relation \(f_1(x) = u\) in \(\Phi\). It turns out that we can regard \(\{\phi_0(x), \cdots, \phi_r(x)\}\) as a free basis of the \(O_S\) module,

\[\Phi(s) = O_{\bar{X} \times S}(F_2(x, t), \cdots, F_k(x, t)) + I_{C_0}(t).\]

Under this situation, we introduce holomorphic functions \(\tau_{ij}(s) \in O_S\) in the following way.

\[(3.2) \quad \phi_i(x) c_j(x) = \sum_{\ell=0}^{r} \tau_{ij}(s) \phi_{i}(x) \ mod(O_{\bar{X} \times S}(\delta F(x, s)_{x_1}, \cdots, \delta F(x, s)_{x_n})).\]

The functions \(\tau_{ij}(s) \in O_S\) exist due to the versality of the deformation \(\bar{F}(x, s)\). We denote by

\[(3.3) \quad T_{ij}(s) = (\tau_{ij}(s))_{0 \leq i, j \leq r},\]

a \(\mu \times \mu\) matrix which is called the matrix of multiplication table. We denote the discriminant associated to this deformation by \(D \subset S\).

Further on we will make use of the abbreviation \(\text{mod}(d_x \bar{F}(x, s))\) instead of making use of the expression \(\text{mod}(O_{\bar{X} \times S}(\delta F(x, s)_{x_1}, \cdots, \delta F(x, s)_{x_n})).\)

After Proposition 2.4 the vector field \(\vec{e}_1\) constructed in Lemma 2.6 has its lifting \(\vec{v}_1 \in Der_{\bar{X} \times S}.\) Let us denote by \(\vec{v}_1 = \vec{v}_1 - \vec{v}_1 \in O_{\bar{X} \times S} \otimes Der_{\bar{X}}.\)

\[\vec{v}_1(\bar{F}(x, s)) \cdot \phi_1(x) = \vec{v}_1(\bar{F}^{0}(x)) \cdot \phi_1(x) + \sum_{\ell=0}^{r} \vec{v}_1(s_\ell) \vec{e}_\ell(x) \phi_1(x) + \sum_{\ell=0}^{r} s_\ell(\vec{v}_1 \vec{e}_\ell(x)) \phi_1(x)\]

\[\equiv \sum_{\ell=0}^{r} \vec{v}_1(s_\ell) \vec{e}_\ell(x) \phi_1(x) \ mod(d_x \bar{F}(x, s)).\]

**Lemma 3.1** There exists a vector valued function \(M(x, \bar{F}(x, s)) \in (O_{\bar{X} \times C_k})^k\) such that

\[\vec{v}_1(s)(\bar{F}(x, s)) = M(x, \bar{F}(x, s)) \ mod(d_x \bar{F}(x, s)),\]

with

\[M(x, \bar{F}(x, s)) = M^0 \cdot \bar{F}(x, s) + M^1(x, \bar{F}(x, s)),\]

where \(M^0 \in GL(k, C)\): a non-degenerate matrix and \(M^1(x, \bar{F}(x, s)) \in (O_{\bar{X}} \otimes m^2_k)^k\). Especially the first row of \(M^0 = (1, 0, \cdots, 0)\).

**Proof** First of all we remember a theorem due to [5] §1.1, [13] Proposition 2.3.2 which states that the Krull dimension of the ring of holomorphic functions on the critical set \(Cr(\bar{F})\) is equal to \(\mu - 1\) and this ring is a Cohen- Macaulay ring. Let us denote by \(L = n C_k.\) We have \((k + L)\) tuple of \(k \times k\)- minors \(j_{k+1}(x, s) \cdots j_{k+L}(x, s)\) of the matrix \((\delta_{x_1} F(x, s), \cdots, \delta_{x_n} F(x, s))\) such that

\[Cr(\bar{F}) = V(< F_1(x, s), \cdots, F_k(x, s), j_{k+1}(x, s), \cdots, j_{k+L}(x, s) >).\]
The lemma 2.6 yields that the lifting \( \vec{v}_1 \) of the vector field \( \vec{v}_1 \) satisfies the relations,

\[
\langle F_1(x, s), \ldots, F_k(x, s), j_{k+1}(x, s), \ldots, j_{k+L}(x, s) \rangle
= \langle \vec{v}_1(F_1(x, s)), \ldots, \vec{v}_1(F_k(x, s)), \vec{v}_1(j_{k+1}(x, s)), \ldots, \vec{v}_1(j_{k+L}(x, s)) \rangle.
\]

As it has been seen above Proposition 2.4, the vector \( \vec{v}_1 \) prop2 is tangent to \( \mathcal{C} \cap (\vec{F}) \). If the above equality does not hold, it would entail the relation

\[
D = \{ s \in S; \Delta(s) = 0 \} \subseteq \pi(V(< \vec{v}_1(F_1(x, s)), \ldots, \vec{v}_1(F_k(x, s)), \vec{v}_1(j_{k+1}(x, s)), \ldots, \vec{v}_1(j_{k+L}(x, s))>)\},
\]

after elimination theoretical consideration. This yields

\[
\vec{v}_1(F_q(x, s)) = \sum_{\ell=1}^{k} C_{q}^{\ell} F_{\ell}(x, s) + m_q(x, \vec{F}) + \sum_{\ell=k+1}^{k+L} C_{p}^{\ell} j_{p}(x, s), 1 \leq q \leq k,
\]

\[
\vec{v}_1(j_{p}(x, s)) = \sum_{\ell=k+1}^{k+L} C_{p}^{\ell} j_{p}(x, s), k + 1 \leq p \leq k + L,
\]

for \( m_q(x, \vec{F}) \in \mathcal{O}_R \otimes \mathcal{M}^2_2, 1 \leq q \leq k \) and some constants \( C_{q}^{\ell}, 1 \leq \ell \leq k \). First we see that the expression \( \vec{v}_1(j_{p}(x, s)) \) cannot contain terms of \( F_q(x, s) \) like \( F_q(0, s) \) in view of the situation that the versality of the deformation makes all linear in \( x \) variable terms dependent on some of deformation parameters. Secondly the non-degeneracy of the matrix \( M^0 := (C_{q}^{\ell})_{1 \leq q, \ell \leq k} \) is necessary so that the above equality among ideals holds.

From this relation and the preparation theorem, we see

\[
\vec{v}_1(\vec{F}(x, s)) = M^0 \cdot \vec{F}(x, s) + M^1(x, \vec{F}(x, s)) + h_{1,1}(x, s) \frac{\partial \vec{F}(x, s)}{\partial x_1} + \cdots + h_{1,n}(x, s) \frac{\partial \vec{F}(x, s)}{\partial x_n},
\]

with \( M^1(x, \vec{F}(x, s)) = (m_1(x, \vec{F}), \ldots, m_k(x, \vec{F})) \).

More precisely we can state that \( C_1^1 = 1, C_1^\ell = 0, 2 \leq \ell \leq k \). The dependence of some coefficients of \( \vec{v}_1 \) on \( F_l(x, t) \) is necessary so that \( C_1^\ell \neq 0 \) for some \( 2 \leq \ell \leq k \). But this is impossible because if not it would mean that some of the coefficients of \( \vec{v}_1 \) contains factor \( F_1(x, s), \ldots, F_k(x, s) \) that contradicts the construction of \( \vec{v}_1 \) in Proposition 2.4. This can be seen from the fact that the expressions \( \frac{\partial F_1(x, s)}{\partial x_1}, \ldots, \frac{\partial F_k(x, s)}{\partial x_k}, \frac{\partial F_1(x, s)}{\partial x_1}, \ldots, \frac{\partial F_k(x, s)}{\partial x_k} \) do not contain the deformation parameters present in the polynomials \( F_2(x, s), \ldots, F_k(x, s) \). Q.E.D.

**Lemma 3.2** A basis of logarithmic vector fields \( \vec{v}_0, \ldots, \vec{v}_r \in \text{Der}_S(\log D) \) can be produced from the functions \( \sigma_i^j(s) \) defined as follows,

\[
M(x, \vec{F}(x, s)) \cdot \phi_i(x) = \sum_{\ell=0}^{r} \sigma_i^\ell(s) \vec{e}_\ell + \vec{v}_i(\vec{F}(x, s))
\]

where the vector valued function \( M(x, \vec{F}(x, s)) \) denotes the one defined in the Lemma 3.1 and \( \vec{v}_i = \sum_{p=1}^{n} h_{j,p}(x, s) \frac{\partial}{\partial x_p} \) is a certain vector field with holomorphic coefficients.
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Proof

We remark the following relation,

$$
\hat{v}_1(\vec{F}(x, s))\phi_i(x) = \hat{v}_1(\vec{F}(0)(x))\phi_i(x) + \sum_{j=1}^{\mu} \hat{v}_1(s_j)\vec{e}_j(x)\phi_i(x) + \sum_{j=1}^{\mu} s_j\hat{v}_1(\vec{e}_j(x))\phi_i(x)
$$

$$
\equiv \sum_{j=0}^{r} \hat{v}_1(s_j)\vec{e}_j(x)\phi_i(x) \mod(d_x\vec{F}(x, s)).
$$

The relation (3.2) above entails,

$$
M(x, \vec{F}(x, s)) \cdot \phi_i(x) \equiv \sum_{\ell=0}^{r} \sum_{j=0}^{r} \hat{v}_1(s_j)\tau_{i,j}^{\ell}(s)\vec{e}_\ell(x) \mod(d_x\vec{F}(x, s)).
$$

As $\phi_i(x)$ can be considered to be a basis of $O_S$ module $\Phi(s)$ above, vectors $(\sigma_1^0(s), \cdots, \sigma_1^r(s))$, $0 \leq i \leq r$, are $O_S$ linearly independent at each generic point $S \backslash D$. If we put

$$
\sigma_i^\ell(s) = \sum_{j=0}^{r} \hat{v}_1(s_j)\tau_{i,j}^{\ell}(s),
$$

then the vector field $\hat{v}_i \in Der_{\overline{X} \times S}$

$$
\hat{v}_i = \sum_{\ell=0}^{r} \sigma_i^\ell(s) \frac{\partial}{\partial s_\ell} + \phi_i(x)\hat{v}_1,
$$

is tangent to $Cr(\vec{F})$. The only non-trivial relations that may arise between $\hat{v}_i$ and $\hat{v}_{i'}$ $i \neq i'$ is

$$
\phi_i(x)\hat{v}_{i'} = \phi_{i'}(x)\hat{v}_i.
$$

These vectors give rise to the same push down vector field in $Der_S(\log D)$. Namely,

$$
\pi_* (\phi_i(x)\hat{v}_{i'}) = \pi_* (\phi_{i'}(x)\hat{v}_i) = \sum_{j=0}^{r} \sum_{\ell=0}^{r} R_{i,i',j}^{\ell}(s) \frac{\partial}{\partial s_\ell},
$$

for the coefficients $R_{i,i',j}^{\ell}(s)$ determined by

$$
\sum_{j=0}^{r} \hat{v}_1(s_j)\phi_i(x)\phi_{i'}(x)\vec{e}_j(x) \equiv \sum_{j=0}^{r} \sum_{\ell=0}^{r} R_{i,i',j}^{\ell}(s)\vec{e}_\ell(x) \mod(d_x\vec{F}(x, s)).
$$

This means that $\hat{v}_0, \cdots, \hat{v}_r$ form a free basis of $Der_{\overline{X} \times S}(Cr(\vec{F}))$ hence $\hat{v}_0, \cdots, \hat{v}_r$ that of $Der_S(\log D)$.

Q.E.D.

This lemma gives us a correspondence between $\phi_i(x) \in \Phi$ and $\hat{v}_i \in Der_S(\log D)$, therefore it is quite natural to expect that the mixed Hodge structure on $\Phi$ would induce that on $Der_S(\log D)$, and would hence contribute to describe $B_{1}(s)$ of Theorem 2.7, 1 in a precise manner. A good understanding of this situation is indispensable to characterize the rational monodromy of solutions to the Gauss-Manin system in terms of the mixed Hodge structure on $\Phi$.

Proposition 3.3 There exist holomorphic functions $w_{j}(s) \in O_{S}, 0 \leq j \leq \tau$ such that the components of the matrix

\[ \Sigma(s) := \sum_{j=0}^{\tau} w_{j}(s)T_{j}(s), \]

give rise to a basis of logarithmic vector fields $\tilde{v}_{0}, \cdots, \tilde{v}_{\tau} \in Ders(\log D)$. Namely, if we write $\Sigma(s) = (\sigma_{1}^{\ell}(s))_{0 \leq i, \ell \leq \tau}$, then the expression

\[ \tilde{v}_{\ell} = \sum_{\ell=0}^{\tau} \sigma_{i}^{\ell}(s) \frac{\partial}{\partial s_{\ell}}, \]

consists a base element of the $O_{S}$ module $Ders(\log D)$.

Especially in the case of quasihomogeneous singularity $f(x, u)$ we have the following simple description of the vector field that can be deduced from Lemma 3.2. To do this, it is enough to remark that the vector field $\tilde{v}_{1}$ is the Euler vector field by definition and $\tilde{v}_{1}(s_{\tau}) = \frac{w\left(s_{\tau}\right)}{w\left(s_{0}\right)}$, where $w(s_{j})$ denotes the quasihomogeneous weight of the variable $s_{j}$.

Proposition 3.4 ([4] Theorem 2.4) In the case of quasihomogeneous singularity (2.1), the basis (3.5) of $Ders(\log D)$ can be calculated by

\[ \sigma_{1}^{\ell}(s) = \sum_{j=0}^{\tau} w(s_{j}) s_{j} \tau_{i,j}^{\ell}(s). \]

Furthermore, the vector valued function $M(x, \overline{F}(x, s))$ of Lemma 3.1 has the expression,

\[ M(x, \overline{F}(x, s)) = M^{0} \cdot \overline{F}(x, s) = \text{diag}(w(f_{1}), \cdots, w(f_{k})) \cdot \overline{F}(x, s). \]

4 Multiplication table and the topology of real hypersurfaces

In this section we continue to consider the situation where $\mu = \tau + 1$ for $k = 1$ in (2.5). We associate to the versal deformation of the hypersurface singularity

\[ F(x, s) = f(x) + \sum_{i=0}^{\tau} s_{i}e_{i}(x), \]

the following matrix $\Sigma(s) = (\sigma_{1}^{\ell}(s))_{0 \leq i, \ell \leq \tau}$ after the model (3.2),

\[ F(x, s)e_{i}(x) = \sum_{\ell=0}^{\tau} \sigma_{i}^{\ell}(s)e_{\ell}(x) \mod(d_{x}F(x, s)) \]

and

\[ e_{i}(x)e_{j}(x) = \sum_{\ell=0}^{\tau} \tau_{i,j}^{\ell}(t)e_{\ell}(x) \mod(d_{x}F(x, s)). \]
Further on we make use of the convention $e_0(x) = 1$ and $s = (s_0, t)$. We will denote the deformation parameter space $t \in T = (\mathbb{C}^\tau, 0)$.

We recall the Milnor ring for $k = 1$ whose analogy has been introduced in (2.5),

$$Q_F := \mathcal{O}_{\overline{X} \times S}/(\mathcal{O}_{\overline{X} \times S} \cdot \partial F(x, s)/\partial x_1, \ldots, \partial F(x, s)/\partial x_n).$$

We introduce the Bezoutian matrix $B^F(s)$ whose $(i, j)$ element is defined by the trace of the multiplication action $F(x, s)e_i(x)e_j(x)$ on the Milnor ring $Q_F$,

$$F(x, s)e_i(x)e_j(x) \equiv \sum_{c=0}^{\tau} \sigma_i^c(s)e_{c}(x)e_j(x) \mod(d_xF(x, s)).$$

For the sake of simplicity we will use the following notation,

$$\tau^f(t) = (\tau_{b,c}^f(t))_{0 \leq b, c \leq \tau}.$$

To clarify the structure of the Bezoutian matrix $B^F(s)$ we introduce a matrix

$$T(t) = \left( \sum_{r=0}^{\tau} \zeta_r(t) \tau^r(t) \right),$$

with the notation

$$\zeta_r(t) = \text{tr}(e_r(x)) = \sum_{e=0}^{\tau} \tau_{r,e}^e(t).$$

The $(i, j)$ element of the matrix $T(t)$ (4.5) equals to $\text{tr}(e_i(x)e_j(x))$ on the Milnor ring $Q_F$. It is possible to show that $\{ t \in T; \det(T(t)) = 0 \}$ coincides with the bifurcation set of $F(x, s)$ outside the Maxwell set. Thus we get the Bezoutian matrix

$$B^F(s) = \Sigma(s) \cdot T(t).$$

Following statement is a simple application of Morse theory to the multiplication table see [14] Theorem 2.1. From here on we assume that $|s|$ is small enough and denote by $\tilde{X} = \{ x \in \mathbb{C}^n; |x| \leq \delta \}$ a closed ball such that all critical points of $F(x, s)$ are located inside $\tilde{X}$.

**Proposition 4.1** Sign $\Sigma(s) \cdot T(t) =$ \{ number of real critical points with respect to the variables $x$ in $F(x, s) > 0, x \in \tilde{X} \cap \mathbb{R}^n$ \} - \{ number of real critical points with respect to the variables $x$ in $F(x, s) < 0, x \in \tilde{X} \cap \mathbb{R}^n$ \}. Here sign$(A)$ denotes the signature of a symmetric matrix $A$ i.e. the difference between the number of positive and negative eigenvalues.

Let us denote by $h(x, t)$ the determinant of the Hessian

$$h(x, t) := \det(\partial^2 F(x, s)/\partial x_i \partial x_j)_{1 \leq i, j \leq n}.$$

We associate the following $\mu$ holomorphic functions $h_0(t), \ldots, h_{\tau}(t) \in \mathcal{O}_S$ to the function $h(x, t)$,

$$h(x, t) \equiv \sum_{\ell=0}^{\tau} h_{\ell}(t) e_{\ell}(x) \mod(d_xF(x, s)).$$
Further by means of (4.7) we introduce the matrix

\begin{equation}
B^H(t) := \sum_{\ell=0}^{\tau} \eta^\ell(t) \tau^\ell(t).
\end{equation}

where

\[
\begin{pmatrix}
\eta^0(t) \\
\vdots \\
\eta^\ell(t)
\end{pmatrix} = T(t) \cdot 
\begin{pmatrix}
h_0(t) \\
\vdots \\
h_\tau(t)
\end{pmatrix},
\]

We consider the matrix $B^{HF}(s) = (\cdot)_{0 \leq a,b \leq \tau}$ whose $(a,b)$-element is defined by the trace of the following expression on the Milnor ring $Q_F$,

\begin{equation}
\sum_{\ell=0}^{\tau} \sum_{c=0}^{r} \sigma_c^\ell(s) \tau_{c,b}^m(t) e_{m}(x).
\end{equation}

If we take the trace of this, we get

\[
\sum_{c=0}^{r} \sigma_c^\ell(s) \tau_{c,b}^m(t) \sum_{r=0}^{\tau} \tau_{\ell,m}^f(t) \zeta_r(t)).
\]

After (4.8) and (4.9) this matrix has the following expression,

\begin{equation}
B^{HF}(s) = \Sigma(s) \cdot B^H(t).
\end{equation}

We consider the following closures of semi-algebraic sets,

\[W_{=0} := \{ x \in \tilde{X} \cap \mathbb{R}^n; F(x,s) = 0 \}, \]

\[W_{\geq 0} := \{ x \in \tilde{X} \cap \mathbb{R}^n; F(x,s) \geq 0 \}, W_{\leq 0} := \{ x \in \tilde{X} \cap \mathbb{R}^n; F(x,s) \leq 0 \}.
\]

**Theorem 4.2** The following expression of the Euler characteristics for $W_*$ holds,

\[
\chi(W_{\geq 0}) - \chi(W_{=0}) = \frac{\text{sign}(B^H(t)) + \text{sign}(B^{HF}(s))}{2},
\]

\[
\chi(W_{\leq 0}) - \chi(W_{=0}) = (-1)^n \frac{\text{sign}(B^H(t)) - \text{sign}(B^{HF}(s))}{2}.
\]

**Proof**

After Szafraniec [14], or simply applying Morse theory to the real fibres of $F(x,s)$, we have the following equalities,

\[
\sum_{x \in \text{critical points of } F(x,s)} (\text{sign } h(x,t))
\]
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\[ = \text{sign}(tr(h(x, t)e_i(x) \cdot e_j(x)))_{1 \leq i, j \leq n} = \sum_{x \in \text{critical points of } F(x, s)} (-1)^{\lambda(x)}. \]

Here we denoted by \( tr(h(x, t)e_i(x) \cdot e_j(x)) \) the trace of a matrix defined by the multiplication by the element \( h(x, t)e_i(x) \cdot e_j(x) \) considered mod \( (d_x F(x, s)) \) for the basis \( e_i(x), 1 \leq i \leq \mu \).

\[ = \text{sign}(tr(h(x, t)F(x, s)e_i(x) \cdot e_j(x)))_{1 \leq i, j \leq n} = \sum_{x \in \text{critical points of } F(x, s)} (-1)^{\lambda(x)}(\text{sgn} F(x, s)). \]

Here we denoted by \( tr(h(x, t)F(x, s)e_i(x) \cdot e_j(x)) \) the trace of a matrix defined by the multiplication by the element \( h(x, t)F(x, s)e_i(x) \cdot e_j(x) \) considered mod \( (d_x F(x, s)) \) for the basis \( e_i(x), 1 \leq i \leq \mu \).

Here \( \lambda(x) \) is the Morse index of the function \( F(x, s) \) at \( x \) and \( h(x, t) = (-1)^{\lambda(x)} \).

Q.E.D.

References


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