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Cyclic covers of Stable curves and their moduli spaces

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Cyclic covers of Stable curves and their moduli spaces (*)

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Abstract. — We study the deformation of $G$-marked stable curves in the case where $G$ is a cyclic group, and construct a parameterizing space for $G$-marked stable curves of a given numerical type.

This is then used in order to study the components of the locus of stable curves admitting the action of a cyclic group of non prime order $d$, extending the work of F. Catanese in the case where $d$ is prime.

Résumé. — Nous étudions la déformation des courbes stables marquées de $G$ dans le cas où $G$ est un groupe cyclique et construisons un espace de paramétrage pour les courbes stables marquées par $G$ d’un type numérique donné.

Ceci est ensuite utilisé afin d’étudier les composantes de l’ensemble des courbes stables en admettant l’action d’un groupe cyclique de non-premier ordre $d$, extension du travail de F. Catanese dans le cas où $d$ est premier.

Introduction

The purpose of this article is to study the structure of the locus $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$ of (non-smooth) stable curves of genus $g$ inside the compactified moduli space $\overline{\mathcal{M}}_g$ admitting an effective action by a cyclic group $G$.

In [4] and [5] M. Cornalba determined the irreducible components of $\text{Sing}(\overline{\mathcal{M}}_g)$, the singular locus of the moduli scheme of smooth projective
curves of genus $g \geq 2$. The result was obtained by showing that $\mathcal{M}_g(\mathbb{Z}/p)$, the locus inside $\text{Sing}(\mathcal{M}_g)$ of curves admitting an effective action by a cyclic group of prime order $p$, is irreducible and maximal (i.e., being not contained in another locus) except for finitely many cases. The main ingredient Cornalba used is that the locus corresponding to cyclic covers of prime order of smooth curves with a fixed combinatorial datum, called the numerical type (see Definition 2.1), is an irreducible Zariski closed subset of the moduli space $\mathcal{M}_g$. Catanese in [1] extended this result to the case of cyclic groups of any order (cf. Theorem 2.3).

The studies of such loci can be continued in two directions:

In one direction more finite groups $G$ are considered. For instance the case where $G = D_n$, the dihedral group of order $2n$, was investigated in a series of papers by F. Catanese, M. Lønne and F. Perroni (cf. [2, 3]) and later by B. Li and S. Weigl (cf. [7]). The main difficulty there is that for general groups a numerical type might correspond to a reducible subset of the moduli space. In [3] the authors introduced a new homological invariant which enables them to distinguish the irreducible components asymptotically (i.e., when the genus of the quotient curve $\gg 0$).

The other direction is to consider the boundary of the compactified moduli space $\overline{\mathcal{M}}_g$. In [1], Catanese determined the irreducible components of $\text{Sing}(\overline{\mathcal{M}}_g - \mathcal{M}_g)$ by studying the loci $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(\mathbb{Z}/p)$ and obtained analogous results as in the smooth case. In this case, the locus of stable curves with a given numerical type is not necessarily Zariski closed: if a stable curve $C_1$ is smoothable to another stable curve $C_2$, then the corresponding locus of $C_1$ is contained in the closure of that of $C_2$, hence one should look at the non-smoothable stable curves. Hence in the boundary case the notion of maximal means that the Zariski closure of the locus is maximal (cf. Definition 2.13).

In this article we go into both directions, studying the loci $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(\mathbb{Z}/d)$ of non-prime order $d$ and generalize several results in [1].

This article is organized as follows.

In Section 1 we give the definition of a $G$-marked stable curve (i.e., a stable curve $C$ admitting an effective action by a finite group $G$, cf. Definition 1.1) and associated notions.

In Section 2 we study the $G$-equivariant deformation (cf. Definition 2.4) of $G$-marked stable curves, and determine when a $G$-marked stable curve is $G$-equivariantly smoothable. Then we define the associated numerical type for $G$-marked stable curves and prove the main result of this section that, for $G$-marked stable curves with a given numerical type, there is a parameterizing space (cf. Theorem 2.11):
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Theorem A. — Given a G-marked stable curve \((C,G,\rho)\), there exists a connected complex manifold \(T_{[D(C,G,\rho)]}\) parameterizing all G-marked stable curves with numerical type \([D(C,G,\rho)]\).

If moreover \((C,G,\rho)\) is G-equivariantly non-smoothable, denoting by \(M_{[D(C,G,\rho)]}\) the image of the natural morphism \(T_{[D(C,G,\rho)]} \to M_g - M_g\), then each point inside \(M_{[D(C,G,\rho)]}\) has finite inverse image in \(T_{[D(C,G,\rho)]}\), and the closure \(\overline{M}_{[D(C,G,\rho)]}\) consists of G-marked stable curves which can be G-equivariantly deformed into a curve with numerical type \([D(C,G,\rho)]\).

In Section 3 we study the irreducible components of \((M_g - M_g)(G)\) for the case \(G = \mathbb{Z}/d\), the idea is to determine when a G-stratum (i.e., the image inside \((M_g - M_g)(\mathbb{Z}/d)\) of the parameterizing space of a given numerical type, cf. Definition 2.13) is maximal. For this we need to compare all the order \(d\) cyclic subgroups of the stratum (cf. Definition 3.2).

Due to some phenomena arising from the smooth case (cf. Proposition 3.5), the automorphism group of a stratum might become very complicated, making it impossible to give a brief and explicit description for maximal strata. Hence we make some technical assumptions.

Assumption (cf. Assumption 3.6).

1. \((C = \sum_{i \in I} C_i, G, \rho)\) is G-equivariantly non-smoothable.
2. For a general stable curve \((C,G,\rho)\) in the stratum we have \(H_i = \text{Aut}(\tilde{C}_i)\) and \(g(\tilde{C}_i) \geq 2\) for all \(i\).
3. For any \(i \in I\), the parameterizing space \(\mathcal{T}_{h_i,r_i}\) has dimension \(> 0\).

With the above assumptions we prove the main result of this article (cf. Theorem 3.17):

Theorem B. — Under the conditions of Assumption 3.6, we have the following:

1. For a G-equivariantly non-smoothable G-marked stable curve \((C = \sum_{i \in I} C_i, G, \rho)\), the induced stratum \(\mathcal{M}_{C'}\), where \(C' = C/G\), is maximal iff for a general stable curve (by abuse of notation we denote still by) \((C,G,\rho)\) in the stratum:
   a. The cases in Lemma 3.10 do not occur.
   b. For any \(\beta \in \text{Aut}(C)\) (of order \(d\)) and any node \(p\) where Case (II-i) happens (cf. page 58), the following holds:
      \[ c_{p,1}^{b(p,1)c(\beta,p,1)} c_{p,2}^{b(p,2)c(\beta,p,2)} \neq 1. \]
   c. For any \(\beta \in \text{Aut}(C)\) (of order \(d\)), there is no node \(p\) of type E with respect to \(\beta\) (see Definition 3.16).
(2) The Zariski closure of each maximal stratum in (1) is an irreducible component of \((\overline{M}_g - \overline{M}_g)(G)\).

1. Notation

Let \(C\) be a (non-smooth) stable curve (i.e., \(C\) has at most nodes as singularities and \(\text{Aut}(C)\), the automorphism group of \(C\), is finite),

\[ C = \sum_{i \in I} C_i. \]

We define \(I\) to be the graph whose set of vertices is the set \(I\), and whose set of edges is the set \(\mathcal{N}\) of the nodes \(P \in C\).

We let \(\mathcal{N}_i := \mathcal{N} \cap C_i\), i.e., these are the edges of the graph containing the vertex \(i\).

Note that if \(P \in \mathcal{N}, P \in C_i \cap C_j, i \neq j\), then \(P\) yields an edge connecting two distinct vertices, else, if \(P \in C_i\) and \(P \notin C_j, \ \forall j \neq i\), \(P\) yields a loop based at \(i\). Hence we have

\[ \mathcal{N}_i = N_i^{(1)} \cup N_i^{(2)}, \]

where \(N_i^{(1)}\) corresponds to edges connecting two distinct vertices (one of the vertex is \(i\)) and \(N_i^{(2)}\) corresponds to loops based at \(i\).

Set further \(C - C_i = \overline{C \setminus C_i}\).

**Definition 1.1.**

(1) Let \(G\) be a finite group. A \(G\)-marked stable curve is a triple \((C, G, \rho)\), where \(C\) is a stable curve, \(\rho : G \hookrightarrow \text{Aut}(C)\) is an injective homomorphism, i.e., \(G\) acts effectively on the stable curve \(C\). When \(\rho\) is clear, for instance if \(G\) is a subgroup of \(\text{Aut}(C)\), we write for short \((C, G)\) instead of \((C, G, \rho)\).

(2) We call \((C, G, \rho)\) a smooth (resp. irreducible) \(G\)-marked curve if \(C\) is smooth (resp. irreducible).

**Remark 1.2.** — In the case where \(\rho\) is clear from the context, we identify \(G\) with its image \(\rho(G)\) and write \(G \subset \text{Aut}(C)\).

Given a \(G\)-marked curve \((C, G, \rho)\), then \(G\) acts naturally on the graph \(I\), and on the set \(I\).
Definition 1.3.

(i) Let $K_v$ be the kernel of the action on $I$, and let instead $G_i$ be the stabilizer of $i \in I$; in other words,

$$G_i := \{ g \mid g(C_i) = C_i \}$$

and $K_v = \bigcap_{i \in I} G_i$.

(ii) Let $K$ be the kernel of the action on the graph $I$, and let, for $P \in \mathcal{N}$, $G_P$ be the stabilizer of $P$; hence $K = K_v \cap (\bigcap_{P \in \mathcal{N}} G_P)$. We let moreover $G_i'$ be the subgroup of $G_i$ which fixes the nodes in $\mathcal{N}_i$, the nodes of $C$ belonging to $C_i$, and we let $G_i''$ be the subgroup which acts trivially on $C_i$. Hence $K = \bigcap_{i \in I} G_i'$. We denote by $n_i$ the order of $G/G_i'$.

(iii) In the case $G$ is an abelian group, let $H_i$ be the quotient group $G_i/G_i''$, respectively $H_i' := G_i'/G_i''$. Necessarily $H_i'$ is a cyclic subgroup if $\mathcal{N}_i \neq \emptyset$. We denote by $d_i$ (resp. $d_i'$) the order of $H_i$ (resp. $H_i'$).

(iv) Setting where $I_0 = \{ i \in I \mid G = G_i'' \}$, $I_1 = \{ i \in I \mid G = G_i \text{ and } G \neq G_i'' \}$ and $I_2 = \{ i \in I \mid G \neq G_i \}$, then the set $I$ has a natural partition $I = I_0 \cup I_1 \cup I_2$.

In the rest of this article $G$ shall denote a cyclic group $\mathbb{Z}/d$ with generator $\gamma$ and $\zeta_d := \exp \left( \frac{2\pi \sqrt{-1}}{d} \right)$. We work over the field of complex numbers $\mathbb{C}$.

2. Parametrizing space of cyclic coverings

In this section we will construct parameterizing spaces for $G$-marked stable curves, first we review the case of smooth $G$-marked curves.

Let $(C, G)$ be a smooth irreducible $G$-marked curve. The action of $G$ on $C$ induces a (ramified) covering map $C \to C' := C/G$. For any $1 \leq i \leq d-1$, we define a divisor $D_i$ as the sub-divisor of the branch locus $D \subset C'$ where the local monodromy is $\zeta_d^i$ (cf. [1, p. 4, l. 20]).

Definition 2.1 ([1, Definition 2.2]). — Let $C$ be a smooth irreducible projective curve of genus $g$ on which $G = \mathbb{Z}/d$ acts faithfully, and set $C' = C/G$, $h := \text{genus}(C')$.

Denote by $k_i = \deg(D_i)$ for $i = 1, \ldots, d - 1$, and by $(k_1, \ldots, k_{d-1})$ the branching sequence of $\gamma$. A change of generator of $\mathbb{Z}/d$ corresponds to a $(\mathbb{Z}/d)^*$-action on the set of sequences, we denote the resulting equivalence class by $[(k_1, \ldots, k_{d-1})]$, and call it the numerical type of the cyclic cover $C \to C'$. 

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**Definition 2.2** ([1, Definition 2.3]). — Given a branching datum corresponding to a sequence \([k_1, \ldots, k_{d-1}]\), set
\[
h := 1 + \frac{2(g-1)}{2d} - \frac{1}{2} \sum_{i=1}^{d-1} k_i \left(1 - \frac{\gcd(i,d)}{d}\right).
\]
The branching datum is said to be admissible for \(d\) and \(g\) if the following two conditions are satisfied:

1. \(\sum_{i=1}^{d-1} k_i i \equiv 0 \pmod{d}\),
2. \(h\) is a positive integer; \(h = 0\), \(\gcd\{d, \gcd\{i \mid k_i \neq 0\}\} = 1\).

Note that the branching datum of a cyclic cover \(C \to C'\) is admissible.

The main result for the parameterizing space of smooth \(G\)-marked curves is the following:

**Theorem 2.3** ([1, Theorem 2.4]). — The pairs \((C,G)\), where \(C\) is a complex projective curve of genus \(g \geq 2\), and \(G\) is a finite cyclic group of order \(d\) acting faithfully on \(C\) with a given branching datum \([(k_1, \ldots, k_{d-1})]\) are parametrized by a connected complex manifold \(T_{g,d;[(k_1, \ldots, k_{d-1})]}\) of dimension \(3(h-1) + k\), where \(k := \sum_i k_i\).

The image \(M_{g,d;[(k_1, \ldots, k_{d-1})]}\) of \(T_{g,d;[(k_1, \ldots, k_{d-1})]}\) inside the moduli space \(M_g\) is a closed subset of the same dimension \(3(h-1) + k\).

We will give an analogous result for \(G\)-marked stable curves.

**Definition 2.4.** — Let \((C, G, \rho)\) be a \(G\)-marked stable curve: a \(G\)-equivariant deformation of \((C, G, \rho)\) is a triple \((p : \mathcal{C} \to B, G, \eta)\) such that

1. \(p : \mathcal{C} \to B\) is a deformation of \(C\) over an irreducible base \(B\) with all fibres stable curves and the central fibre \(\mathcal{C}_O \simeq C\ (O \in B)\).
2. \(\eta : G \to \text{Aut}(\mathcal{C})\) is an injective homomorphism inducing an effective action on \(\mathcal{C}\) such that \(p\) is \(G\)-invariant (where the action of \(G\) on \(B\) is trivial) and \(\eta|_{\mathcal{C}_O} \simeq \rho\).

**Definition 2.5.** — We say that a \(G\)-marked stable curve \((C, G, \rho)\) is \(G\)-equivariantly non-smoothable (or has no \(G\)-equivariant smoothing) if \((C, G, \rho)\) cannot be \(G\)-equivariantly deformed to \((C', G, \rho')\) such that \(C'\) has less nodes than \(C\).

We have the following criterion which tells when a \(G\)-marked stable curves is \(G\)-equivariantly non-smoothable, and generalizes the prime case in [1, Lemma 4.3]:

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Proposition 2.6. — Let $P \in C = \sum_i C_i$ be a node, set $G_P := \text{Stab}(P)$ the stabilizer group of $P$ in $G$, then the following are equivalent:

1. All points in $G(P)(:= \text{the orbit of } P)$ can be simultaneously $G$-equivariantly smoothed.
2. The induced group homomorphism $G_P \to GL(E \text{xt}^1(\Omega_C, \mathcal{O}_C)_P) \simeq \mathbb{C}^*$ is trivial.

Proof. — Recall the local to global spectral sequence:

$$0 \longrightarrow \bigoplus_i H^1 \left( \Theta_{C_i}, \left( - \sum_{j \neq i} (C_i \cap C_j) \right) \right) \longrightarrow \text{Ext}^1(\Omega^1_C, \mathcal{O}_C)$$

$$\longrightarrow \bigoplus_{P \in N} \text{Ext}^1(\Omega^1_C, \mathcal{O}_C)_P \longrightarrow 0,$$

where $\Omega^1_C$ is the sheaf of differentials of $C$ and $\Theta_{C_i}$ denotes the tangent sheaf of $C_i$.

Here I shall explain why the first term of $(\ast)$ has this form, since in the original sequence the first term should be $H^1(\mathcal{H}\text{om}(\Omega_C, \mathcal{O}_C))$. Denote by $\iota_i : C_i \to C$ the natural embedding. As $C$ has only nodes as singularities, a local computation yields the following exact sequence:

$$0 \longrightarrow \Omega_C \longrightarrow \bigoplus_{i \in I} \iota_i^* (\Omega_C) \longrightarrow Q \longrightarrow 0$$

and

$$\iota_i^* \Omega_C \simeq \Omega_{C_i} \oplus Q_i,$$

where $Q$ (resp. $Q_i$) is supported on the nodes of $C$ (resp. $\sum_{j \neq i} C_j \cap C_i$). Now applying the dual functor $\mathcal{H}\text{om}(-, \mathcal{O}_C)$, since $Q$ and $Q_i$ are supported on 0-dimensional sets, we have

$$0 \longrightarrow \mathcal{H}\text{om} \left( \bigoplus_{i \in I} \iota_i^* \Omega_{C_i}, \mathcal{O}_C \right) \longrightarrow \mathcal{H}\text{om}(\Omega_C, \mathcal{O}_C).$$

After some local computation (again note that $C$ has only nodes as singularities), we get the following:

1. $\iota$ is in fact an isomorphism.
2. $\mathcal{H}\text{om}(\iota_i^* \Omega_{C_i}, \mathcal{O}_C) \simeq \iota_i^*(\Theta(- \sum_{j \neq i} C_j \cap C_i)).$

As $H^1(C_i, \Theta_i(- \sum_{j \neq i} C_j \cap C_i)) \simeq H^1(C_i, \iota_i^*(\Theta(- \sum_{j \neq i} C_j \cap C_i)))$, we complete the explanation of the first term of $(\ast)$. 

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The exact sequence (\(\ast\)) remains exact after taking the subspaces of \(G\)-invariant vectors. Hence we have a surjection:

\[
\text{Ext}^1(\Omega_C, \mathcal{O}_C)^G \longrightarrow \left( \bigoplus_{P \in \mathcal{N}} \text{Ext}^1(\Omega_C^1, \mathcal{O}_C)_P \right)^G.
\]

Since \(G_P\) is a subgroup of \(G = \mathbb{Z}/d\), we have \(G_P \simeq \mathbb{Z}/m\) for some \(m|d\), define \(r := m/d\). Denoting by \(\tilde{\gamma}\) the image of \(\gamma\) in \(G/G_P\), clearly \(\tilde{\gamma}\) is a generator of \(G/G_P\). Up to a change of index, we can assume that \(G(P) = \{P_1 = P, \ldots, P_r\}\), such that \(\tilde{\gamma}(P_i) = P_{i+1}\). The surjection (\(\ast\ast\)) means that all combinations of possible local \(G\)-equivariant deformation can be realized by global ones, hence we only need to consider the local deformation at each node \(P\). On the other hand if a \(G\)-equivariant deformation smooths a node \(P\), it must smooth all the points in \(G(P)\) simultaneously. Therefore we see that all points in \(G(P)\) can be simultaneously smoothed \(\iff\exists v = (v_1, \ldots, v_r) \in (\bigoplus_{P_i \in G(P)} \text{Ext}^1(\Omega_C, \mathcal{O}_C)_{P_i})^G\), such that \(v \neq 0\) (since \(v\) is \(G\)-invariant, \(v \neq 0\) is equivalent to \(v_i \neq 0\) for all \(i\)).

Assume \(\gamma(v_1, \ldots, v_r) = (\lambda_r v_r, \lambda_1 v_1, \ldots, \lambda_{r-1} v_{r-1})\) for some \(\lambda_i \in \mathbb{C}^*\). It is easy to see that \(\gamma v = v \iff \prod_{i=1}^r \lambda_i = 1\).

If there exists \(0 \neq v \in (\bigoplus_{P_i \in G(P)} \text{Ext}^1(\Omega_C, \mathcal{O}_C)_{P_i})^G\), then we have \(\gamma v = v\). Noting that \(\gamma^r\) is a generator of \(G_P\), the induced homomorphism \(G_P \rightarrow \mathbb{C}^*\) is then given by \(\gamma^r \mapsto \prod \lambda_i = 1\), hence trivial. Conversely, if \(G_P \rightarrow \mathbb{C}^*\) is trivial, let \(v = (v_1, \lambda_1 v_1, \ldots, (\prod_{i=1}^{r-1} \lambda_i) v_1)\) with \(v_1 \neq 0\), it is clear that \(\gamma v = v\), since \(\prod \lambda_i = 1\). \(\square\)

**Remark 2.7.** — From the proof of Proposition 2.6 we see that a \(G\)-marked curve \(C\) is \(G\)-equivariantly non-smoothable iff \((\bigoplus_{P \in \mathcal{N}} \text{Ext}^1(\Omega_C^1, \mathcal{O}_C)_P)^G = 0\).

**Definition 2.8.** — A \(G\)-marked stable curve \((C, G, \rho)\) has the following associated combinatorial datum \(\mathcal{D}(C, G, \rho)\):

1. A \(G\)-marked graph \((\mathcal{I}, G, \tilde{\rho})\), i.e., the graph \(\mathcal{I}\) with induced \(G\)-action \(\tilde{\rho}\) from the action \(\rho : G \rightarrow \text{Aut}(C)\).
2. For any \(i \in I\), recall that \(H_i = G_i/G_i''\) and \(d_i = \text{Ord}(H_i)\). The image of an element \(\beta \in G_i\) in \(H_i\) is denoted as \(\tilde{\beta}\). We get a \(H_i\)-marked curve \((C_i, H_i, \rho_i)\), denote by \(\tilde{C}_i\) the normalization of \(C_i\) and set \(g_i = \text{genus}(\tilde{C}_i), h_i = \text{genus of } \tilde{C}_i := \tilde{C}_i/H_i\). The element \(\tilde{\gamma}^{n_i}\) generates \(H_i\) (recall that \(n_i = \text{Ord}(G_i/G_i)\)), it induces an action \(\tilde{\rho}_i\) of \(\tilde{H}_i\) on \(\tilde{C}_i\), and hence a branching sequence \((k_1(i), \ldots, k_{d_i-1}(i))\) on \(\tilde{C}_i\).
3. Note that the ramification points of \(\tilde{C}_i\) consists of three parts: (a) points which are not from nodes of \(C\), (b) points which are inverse images of intersection points of two distinct \(C_i, C_j\), and
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(c) points which are inverse images of nodes of some $C_i$. Hence we record the following data:

(a) For each $i \in I_1 \cup I_2$, we record the branching sequence $(k'_1(i), \ldots, k'_{d_i-1}(i))$ corresponding to the ramification points of $\tilde{\rho}_i$ on $\tilde{C}_i$ which are not coming from nodes of $C$.

(b) For each node $p$ which is the intersection of two different components $C_i$ and $C_j$, we record the monodromy $m(p,i)$ (resp. $m(p,j)$) induced by $\gamma_n^i$ (resp. $\gamma_n^j$) at $p$.

(c) For each node $p$ which is a node of some $C_i$, we record the monodromy $n_1(p,i)$ and $n_2(p,i)$ (an unordered pair) induced by $\gamma_n^i$ at $p$.

The automorphism group $\text{Aut}(G) = (\mathbb{Z}/d)^*$ acts naturally on the set of data $\{D(C,G,\rho)\}$, we call the resulting equivalence class, $[D(C,G,\rho)]$ the numerical type of $(C,G,\rho)$.

Remark 2.9.

(1) As in the smooth case, we can determine an “admissible condition” for the above combinatorial data (for the case $G$ has a prime order, see [1, Definition 4.8]), which we will not use in later discussion.

(2) For the $H_i$-marked curve $(\tilde{C}_i, H_i, \rho_i)$, it is important to consider the branching sequence $(k_1(i), \ldots, k_{d_i-1}(i))$ (induced by $\gamma_n^i$) instead of the equivalent $H_i$-class $[(k_1(i), \ldots, k_{d_i-1}(i))]$. Later we will see the differences.

(3) For a non-smoothable $G$-marked curve, using Proposition 2.6, we see that $\forall i \in I_0$, the component $C_i$ is smooth (i.e. $N_i^{(2)} = \emptyset$).

Now we come to the main result of this section, which is a partial generalization of [1, Theorem 4.10].

We denote by Orb the set of $G$-orbits in $I$, for any $o \in \text{Orb}$, we define a subcurve of $C$ consisting of all components in the orbit $o$,

$$C(o) := \bigcup_{i \in o} C_i.$$

We have an induced $G_o := G/G_i''$-marked (nodal)-curve $(C(o), G_o, \rho_o)$ (note that $C(o)$ might be disconnected). The following lemma shows that we have a “canonical form” for $(C(o), G_o, \rho_o)$.

Lemma 2.10. — The $G_o$-marked curve $(C(o), G_o, \rho_o)$ is $G_o$-equivariantly isomorphic to the canonical form $(\bigcup_{j=1}^{n_o} C_o^{(j)}, G_o, \tilde{\rho}_o)$, where $n_o = \#o(= n_i)$, $C_o^{(j)}$ are $n_o$ copies of an irreducible component $C_i$ in $C(o)$, and $\bigcup_{j=1}^{n_o} C_o^{(j)}$ is a
quotient of $\bigsqcup_{j=1}^{n_o} C^{(j)}_o$ by identifying a finite set of (unordered) pair of points $\mathcal{P}_o$ and $\tilde{\rho}_o$ is determined by the following morphisms:

$$\text{id} : C^{(j)}_o \rightarrow C^{(j+1)}_o \quad \forall \ 1 \leq j \leq n_o - 1; \quad \gamma^{j-1} : C^{(n_o)}_o \rightarrow C^{(1)}_o.$$  

**Proof.** — It is clear that the morphisms given in the lemma define an action of $G_o$ on $\bigsqcup_{j=1}^{n_o} C^{(j)}_o$. It is easy to check that the morphisms $\gamma^{j-1}|_{C_i} : C^{(j)}_o(= C_i) \rightarrow \gamma^{j-1}(C_i)$ induce a surjective $G_o$-equivariant morphism $\bigsqcup_{j=1}^{n_o} C^{(j)}_o \rightarrow C(o)$. Denoting by $\mathcal{P}_o$ the set of inverse images of nodes in $C(o)$ which do not have two branches on the same irreducible curve, we obtain a quotient curve $\bigsqcup_{j=1}^{n_o} C^{(j)}_o$ by identifying the pairs of points lying in the same inverse image in $\mathcal{P}_o$, then we have a $G_o$-equivariant isomorphism $\phi_o : \bigsqcup_{j=1}^{n_o} C^{(j)}_o \rightarrow C(o)$, since $C(o)$ is a subset of a stable curve and no three components can meet in a point. $\square$

**Theorem 2.11.** — Given a $G$-marked stable curve $(C, G, \rho)$, there exists a connected complex manifold $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]}$ parameterizing all $G$-marked stable curves with numerical type $[\mathcal{D}(C,G,\rho)]$, i.e., there is a family of $G$-marked curves over $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]}$, such that

(i) each fiber of this family is a $G$-marked stable curves with numerical type $[\mathcal{D}(C,G,\rho)]$,

(ii) every $G$-marked stable curves with numerical type $[\mathcal{D}(C,G,\rho)]$ is $G$-equivariantly isomorphic to a fiber of this family.

Denoting by $\mathcal{M}_{[\mathcal{D}(C,G,\rho)]}$ the image set of the natural morphism $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]} \rightarrow \overline{\mathcal{M}_g} - \mathcal{M}_g$, then each point inside $\mathcal{M}_{[\mathcal{D}(C,G,\rho)]}$ has finite inverse image in $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]}$, and the closure $\overline{\mathcal{M}_{[\mathcal{D}(C,G,\rho)]}}$ consists of curves with a faithful action of $G$ which can be $G$-equivariantly deformed into a curve with numerical type $[\mathcal{D}(C,G,\rho)]$.

If moreover $(C, G, \rho)$ is $G$-equivariantly non-smoothable, then $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]}$ has the same dimension as the Kuranishi space $\text{Ext}^1(\Omega^1_C, O_C)^G$.

**Proof.** — $\mathcal{T}_{[\mathcal{D}(C,G,\rho)]}$ is a product of three products of Teichmüller spaces, corresponding to the partition $I = I_0 \cup I_1 \cup I_2$:

$$\mathcal{T}_0 := \prod_{i \in I_0} \mathcal{T}_{h_i, r_i},$$

where $r_i = |N^{(1)}_i| + 2|N^{(2)}_i|$, and $\mathcal{T}_{h_i, r_i}$ is a parametrizing space of smooth irreducible curves of genus $h_i$ with $r_i$ marked points. Over each $\mathcal{T}_{h_i, r_i}$, we have a family of curves of genus $h_i = g_i$ with $r_i$ marked points.

$$\mathcal{T}_1 := \prod_{i \in I_1} \mathcal{T}_{h_i, r_i},$$

$$\mathcal{T}_2 := \prod_{i \in I_2} \mathcal{T}_{h_i, r_i}.$$
where \( r_i = \sum_{l=1}^{d_i-1} k_l(i) \) is the number of ramification points of the covering \( \tilde{C}_i \to C_i/H_i \). Here \( T_{h_i,r_i} \) coincides with the parametrizing space for smooth \( H_i \)-marked curves of type \( D(\tilde{C}_i,H_i,\tilde{\rho}_i) \) constructed in \cite[Theorem 2.4]{1}, and in the proof of \cite[Theorem 2.4]{1} Catanese has also shown the existence of the family of \( H_i \)-covers with numerical type \( D(\tilde{C}_i,H_i,\tilde{\rho}_i) \) over \( T_{h_i,r_i} \). Hence over each \( T_{h_i,r_i} \) we have a family of \( H_i \)-marked curves of genus \( g_i \) with the branching sequence \((k_1(i),\ldots,k_{d_i-1}(i))\) with respect to a fixed generator \( \gamma_i := \tilde{\gamma} \) of \( H_i \) (See \cite[Theorem 2.4]{1}).

\[
T_2 := \prod_{[i] \in I_2} T_{h_i,r_i},
\]

where \( I_2 \) is the set of orbits in \( I_2 \), \( r_i = \sum_{l=1}^{d_i-1} k_l(i) \). In each orbit \([i]\) we pick one \( T_{h_i,r_i} \), over which we construct a family of \( n_i \) disjoint copies of \( H_i \)-marked curves of genus \( g_i \), with the branching datum \((k_1(i),\ldots,k_{d_i-1}(i))\) with respect to a fixed generator \( \gamma_i := \tilde{\gamma}^{n_i} \) of \( H_i \).

Define

\[
T_{[D(C,G,\rho)]} := T_0 \times T_1 \times T_2.
\]

Now we can glue the pull back of the families over each factor, by identifying the sections according to the numerical type \([D(C,G,\rho)]\), to get a family \( C_{[D(C,G,\rho)]} \) over \( T_{[D(C,G,\rho)]} \).

Each fibre of \( C_{[D(C,G,\rho)]} \) is a stable curve, on which we will define an action of \( G \), making it a \( G \)-marked stable curve with numerical type \([D(C,G,\rho)]\).

We pick a fibre \( C = \sum_{i \in I} C_i \), first we use part (3) of the numerical type \([D(C,G,\rho)]\) to define the action on each orbit of the curves:

If \( i \in I_0 \), \( \gamma \) acts trivially.

If \( i \in I_1 \), we have a natural action of \( H_i \) on \( C_i \) which is induced by the branching datum \((k_1(i),\ldots,k_{d_i-1}(i))\) with respect to \( \gamma_i \), the chosen generator of \( H_i \) (by abuse of notation, the corresponding automorphism is also denoted as \( \gamma_i \)). Then the action of \( G \) is defined by the homomorphism \( G \to H_i \) which sends \( \gamma \) to \( \gamma_i \).

If \( i \in I_2 \), we have to define the action of \( G \) on \( C([i]) \). First we have the action of \( H_i \) on \( C_i \) which is determined by the branching datum \((k_1(i),\ldots,k_{d_i-1}(i))\) with respect to \( \gamma_i \). The action of \( G \), equivalently the automorphism corresponding to \( \gamma \), is defined as follows:

\[
\gamma : C_{\gamma^{l-1}(i)} \to C_{\gamma^{l}(i)}, \quad x \mapsto x \quad \text{if } 1 \leq l \leq n_{[i]} - 1,
\]

\[
\gamma : C_{\gamma^{n_{[i]}-1}(i)} \to C_i, \quad x \mapsto \gamma_i x.
\]

By Lemma 2.10, this should be the expected action.
Then we use conditions (1) and (3) of the numerical type \([D(C, G, \rho)]\) to glue the action on each orbits and obtain an action of \(G\) on \(C\).

For two \(G\)-marked stable curves \((C, G, \rho)\) and \((D, G, \rho')\) with the same numerical type, \(C\) and \(D\) are isomorphic iff for each \(i \in I\), \((\bar{C}_i, H_i, \bar{\rho}_i)\) and \((\bar{D}_i, H_i, \bar{\rho'}_i)\) are isomorphic. In the smooth case, by [1, Theorem 2.4], \(T_{h_i, r_i}\) parametrizes all the \(H_i\)-marked curves with numerical type \([D(\bar{C}_i, H_i, \bar{\rho}_i)]\), hence the same holds for \(T_{[D(C, G, \rho)]}\).

The finiteness of the morphism \(T_{[D(C, G, \rho)]} \to \mathcal{M}_{[D(C, G, \rho)]}\) follows from the stability of curves and the fact that the automorphism group of a stable curve is finite.

If \((C, G, \rho)\) is \(G\)-equivariantly non-smoothable, our parameterizing space has the expected maximal dimension. By Remark 2.7 we have that

\[
\left( \bigoplus_{p \in \mathcal{N}} \mathcal{E}xt^1(\Omega^1_C, \mathcal{O}_C)_p \right)^G = 0.
\]

Taking the \(G\)-invariant subspaces of \((*)\), we get

\[
\left( \bigoplus_i H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right) \right)^G \simeq \mathcal{E}xt^1(\Omega^1_C, \mathcal{O}_C)^G.
\]

It is easy to see that

\[
\left( \bigoplus_i H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right) \right)^G = \bigoplus_{o \in \text{Orb}} \left( \bigoplus_{i \in o} H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right) \right)^G.
\]

For each \(i \in I_0\), it is clear that

\[
H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^G = H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right),
\]

hence has dimension equal to \(\dim_{\mathbb{C}} T_{g_i, r_i}\).

\(\forall i \in I_1\), we have the following:

\[
\dim \left( H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^G \right) = \dim H^1(\Theta_{C_i}(\sim B_i)) = \dim T_{h_i, r_i},
\]

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where $B_i$ is the branching locus of the covering $\tilde{C}_i \to \tilde{C}_i'$. The second equality follows easily from the Riemann–Rock formula, while the first one needs some explanation.

First note that

$$H^1 \left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^G = H^1 \left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^{H_i}.$$

Let $\sigma_i : \tilde{C}_i \to C_i$ be the normalization map, since $C_i$ as only nodes, we have

$$(\sigma_i)_* \Theta_{\tilde{C}_i} \left( - \sum_{p \in \mathcal{N}_i^{(2)}} \sigma_i^{-1}(p) \right) = \Theta_{C_i},$$

here recall that $\mathcal{N}_i^{(2)}$ is the set of nodes which are nodes of $C_i$. Using the projection formula we get

$$(\sigma_i)_* \left( \Theta_{\tilde{C}_i} \left( - \sum_{p \in \mathcal{N}_i^{(2)}} \sigma_i^{-1}(p) - \sum_{j \neq i} C_i \cap C_j \right) \right) = \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right).$$

Since the action of $H_i$ on $\tilde{C}_i$ is induced by the one on $C_i$, we have

$$\dim H^1 \left( \Theta_{\tilde{C}_i} \left( - \sum_{p \in \mathcal{N}_i^{(2)}} \sigma_i^{-1}(p) - \sum_{j \neq i} C_i \cap C_j \right) \right)^{H_i} = \dim H^1 \left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^{H_i}.$$

Therefore the first equality is equivalent to showing

$$\dim H^1 \left( \Theta_{\tilde{C}_i} \left( - \sum_{p \in \mathcal{N}_i^{(2)}} \sigma_i^{-1}(p) - \sum_{j \neq i} C_i \cap C_j \right) \right)^{H_i} = \dim H^1 \left( \Theta_{\tilde{C}_i'}(-B_i) \right),$$

which follows from the following lemma:

**Lemma 2.12.** — Let $\pi : C \to C/G =: C'$ be a cyclic cover of order $d$ between smooth projective curves. Denote by $\mathcal{R}$ (resp. $B$) the ramification divisor (resp. the branching divisor) and $R = \text{Supp}(\mathcal{R})$ (resp. $B = \text{Supp}(B)$) the ramification locus (resp. the branching locus). Let $D \subset R$ be a $G$-invariant effective divisor, then we have

$$H^1(C, \Theta_C(-D))^G \simeq H^1(C', \Theta_{C'}(-B)),$$

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Proof of the lemma. — For any $G$-invariant line bundle $L$ on $C$, we have a decomposition

$$\pi_*(L) = \bigoplus_{i=0}^{d-1} L^{(i)},$$

where we fix a generator $\gamma$ of $G$, $L^{(i)}$ is the $\gamma^i$-eigen-subsheaf of $\pi_*(L)$ (specially, we have $\pi_*(L)^G = L^{(0)}$). Moreover, in this case all $L^{(i)}$ are line bundles on $C'$. Using this decomposition, we have

$$H^1(\pi_*(L))^G = H^1\left(\bigoplus_{i=0}^{d-1} L^{(i)}\right)^G = \left(\bigoplus_{i=0}^{d-1} H^1(L^{(i)})\right)^G = H^1(L^{(0)}). \quad (\star)$$

Recall (dual version of) the Riemann–Hurwitz formula:

$$\Theta_C = \pi^*(\Theta_{C'}) - \mathcal{R}$$

where, setting $e_P$ to be the ramification index at a point $P \in B$ (to be precise, the ramification index should refer to a point $Q \in \pi^{-1}(P)$, but in the case of cyclic covers, for all $Q \in \pi^{-1}(P)$, $e_Q$ remain the same, here we write $e_P$ instead.),

$$\mathcal{R} = \sum_{P \in B} \sum_{Q \in \pi^{-1}(P)} (e_P - 1)Q.$$

Since by assumption $D$ is a reduced divisor, we have

$$\sum_{P \in B} \sum_{Q \in \pi^{-1}(P)} (e_P - 1)Q = \mathcal{R} \leq \mathcal{R} + D \leq \sum_{P \in B} \sum_{Q \in \pi^{-1}(P)} e_P Q = \pi^*(B),$$

therefore

$$\pi^*(\Theta_{C'}) - \pi^*(B) \leq \Theta_C - D \leq \Theta_C = \pi^*(\Theta_{C'}) - \mathcal{R}.$$

Using the fact

$$(\pi_*(\pi^*(\Theta_{C'})) - \pi^*(B)))^G = \Theta_{C'}(-B) \otimes (\pi_* \mathcal{O}_C)^G = \Theta_{C'}(-B) \otimes \mathcal{O}_{C'} = \Theta_{C'}(-B),$$

the statement is then reduced to the case of $D = 0$.

We do local computation to show that $(\pi_*(\Theta_C))^G = \Theta_{C'}(-B)$. Let $P \in B$ and $\pi^{-1}\{P\} = \{Q_1, Q_2, \ldots, Q_s\}$ for some $s|d$ and set $e = d/s$. Let $z$ (resp. $z_1, \ldots, z_s$) be a local coordinate at the point $P$ (resp. $Q_1, \ldots, Q_s$), in local coordinates $\pi$ is expressed as $z = z_i^e$ for $1 \leq i \leq s$. Up to a change of indices and coordinates (see the proof of Lemma 2.10), we may assume the action of $\gamma$ sends $(z_1, \ldots, z_s)$ to $(\zeta_d^i z_s, z_1, \ldots, z_{s-1})$. We compute when a vector field is $G$-invariant, consider $\eta = \sum_i f_i(z_i) \frac{\partial}{\partial z_i}$, then

$$\gamma(\eta) = \sum_{i=1}^{s-1} f_i(z_{i+1}) \frac{\partial}{\partial z_{i+1}} + f_s(\zeta_d^i z_1) \frac{\partial}{\partial z_1}.$$
If $\eta$ is $G$-invariant, we have $f_1(u) = f_2(u) = \cdots = f_s(u)$ and $f_1(u) = f_1(\zeta_i^s u)/\zeta_i^s$. This implies $f_i(u) = u^g(u^e)$ for all $i$, noting that $z_i \frac{\partial}{\partial z_i} = e z \frac{\partial}{\partial z}$, we can rewrite $\eta$ as 

$$
\eta = (e \sum_{i=1}^s g(z_i^e)) z \frac{\partial}{\partial z},
$$

This implies $f_i(u) = \eta$ for all $i$, noting that $z_i \frac{\partial}{\partial z_i} = e z \frac{\partial}{\partial z}$, we can rewrite $\eta$ as 

$$
\eta = \left( e \sum_{i=1}^s g(z_i^e) \right) z \frac{\partial}{\partial z}.
$$

Now we continue the proof of Theorem 2.11.

For each $i \in I_2$, consider the map

$$
H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right) \to \bigoplus_{j \in [i]} H^1\left( \Theta_{C_j} \left( - \sum_{l \neq j} C_j \cap C_l \right) \right)
$$

$$
v \mapsto (v, \gamma(v), \ldots, \gamma_{n_i-1}(v)).
$$

It is easy to see that this induces an isomorphism between the subspaces

$$
H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^H_i \simeq \left( \bigoplus_{j \in [i]} H^1\left( \Theta_{C_j} \left( - \sum_{l \neq j} C_j \cap C_l \right) \right) \right)^G.
$$

Therefore we obtain that

$$
\dim \left( \bigoplus_{j \in [i]} H^1\left( \Theta_{C_j} \left( - \sum_{l \neq j} C_j \cap C_l \right) \right) \right)^G = \dim H^1\left( \Theta_{C_i} \left( - \sum_{j \neq i} C_i \cap C_j \right) \right)^H_i = \dim \mathcal{T}_{h_i,r_i}.
$$

We see that the family $\mathcal{T}_{[D(C,G,\rho)]}$ has the same dimension as the Kuranishi space $\text{Ext}^1(\Omega_C, \mathcal{O}_C)^G$. 

**Definition 2.13.**

1. We call the image of the natural map $\mathcal{T}_{[D(C,G,\rho)]} \to \overline{\mathcal{M}}_g - \mathcal{M}_g$ a stratum with numerical type $[D(C,G,\rho)]$, which we denote by $\mathcal{M}_{[D(C,G,\rho)]}$.

2. A stratum $\mathcal{M}_{[D(C,G,\rho)]}$ is called maximal, if it is not contained in the Zariski closure of another stratum $\overline{\mathcal{M}}_{[D(C',G,\rho')]}$, such that $\dim \mathcal{M}_{[D(C,G,\rho)]} < \dim \mathcal{M}_{[D(C',G,\rho')]}$.

It is clear that $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$ is a union of all the strata (with group $G$). By Theorem 2.11 we see that the closure of any stratum is an irreducible Zariski closed subset of $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$. Therefore to understand the components of $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$, is equivalent to understanding the maximal strata.
Remark 2.14. — Note that when we say a “stratum” we remember the numerical type, the possibility of two strata of different numerical types having the same support is not excluded.

3. The maximal strata

In the previous section we have interpreted the problem of determining irreducible components of \((\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)\) into determining the maximal \(G\)-strata.

In this section we first discuss in general when a stratum is maximal. Then with certain additional conditions we give an explicit description via the associated combinatoric data.

Remark 3.1. — If a stable curve \((C, G, \rho)\) can be smoothed to another stable curve \((C', G, \rho')\), then inside the moduli space, \([C] \notin \mathcal{M}_{[D(C', G, \rho)']}\) and \([C] \in \overline{\mathcal{M}}_{[D(C', G, \rho)']}\), in fact we have a stronger result that 
\[
\mathcal{M}_{[D(C, G, \rho)]} \subset \overline{\mathcal{M}}_{[D(C', G, \rho)']} - \mathcal{M}_{[D(C', G, \rho)']}. 
\]
Hence we have 
\[
\dim \mathcal{M}_{[D(C, G, \rho)]} < \dim \overline{\mathcal{M}}_{[D(C', G, \rho)']}. 
\]

The fact that \(\mathcal{M}_{[D(C, G, \rho)]} \cap \mathcal{M}_{[D(C', G, \rho)']} = \emptyset\) is clear since the number of nodes of \(C'\) is strictly less than that of \(C\), we only need to show \(\mathcal{M}_{[D(C, G, \rho)]} \subset \overline{\mathcal{M}}_{[D(C', G, \rho)']}.\) Note that this is enough to show that general (in fact, every) \([C_1] \notin \mathcal{M}_{[D(C, G, \rho)]}; \) with \([D(C_1, G, \rho_1)] = [D(C, G, \rho)]\), can be deformed \(G\)-equivalently to a curve \((C_2, G, \rho_2)\) such that \([D(C_2, G, \rho_2)] = [D(C', G, \rho')\].

Recall that part (3) of the numerical type remembers the local monodromy at each node \(P\), hence by Proposition 2.6, whether a node is smoothable only depends on the numerical type \([D(C, G, \rho)]\).

For our purpose, it suffices to consider the case where \(C'\) is obtained by smoothing a single orbit \(G(P)\) of some node \(P\). We will see that \([D(C', G, \rho')\] is then uniquely determined by \([D(C, G, \rho)]\).

- Let \(I'\) be the dual graph of \(C'\), then \(I'\) is obtained by contracting the edges in \(I\) which correspond to nodes in \(G(P)\), the action of \(G\) on \(I'\) is then naturally induced from the one on \(I\).
- We denote by \(\text{Con} : I \to I'\) the contraction map. For each vertex \(i' \in I'\), the arithmetic genus associated to \(i'\) (here for \(i'\) we remember the loops based at \(i'\), i.e., the set of nodes \(\Lambda_{i'}^{(2)}\) is just the arithmetic genus of \(\text{Con}^{-1}(i')\). \(G_{i'}\) is the subgroup which leaves the sub-graph \(\text{Con}^{-1}(i')\) invariant and \(G_{i'}''\) is the subgroup which acts trivially on \(\text{Con}^{-1}(i')\), thus we obtain \(H_{i'}\).
Let $G(P) = \{P = P_1, \ldots, P_s\}$, we choose a small $G_P$-invariant analytic open neighborhood $U$ of $P$, such that $\overline{U}$ (here we mean the analytic closure) do not contain any other nodes of $C$ nor fixed points of some $H_i$ on $C_i$. Possibly after shrinking $U$, we require moreover $G(U)$ is a disjoint union of connected $U_1, \ldots, U_s$, each $U_j$ is a connected $G_P$-invariant neighborhood of $P_j$. Then $(C - G(U), G, \rho)$ is $G$-equivariantly isomorphic to a $G$-invariant open subset $V$ of $(C', G, \rho')$, therefore, the fixed points in $V$ with their monodromies, and the monodromy at each node in $V$ are inherited from those on $C - G(U)$, which is determined by $\mathcal{D}(C, G, \rho)$. Note that $C' - V$ is smooth (since it is the local smoothing of $G(P)$ in $G(U)$), we only need to determine the fixed points in $C' - V$ and their monodromies.

Locally the deformation is given by $xy = t$, where $C$ corresponds to $\{t = 0\}$, $P = (0, 0)$ and $C'$ is given by $xy = t_0$ for some $t_0 \neq 0$, fix a generator $\gamma_P$ of $G_P$. There are two cases:

- $G_P$ does not exchange the two branches, the action on the family is given by

$\gamma_P : (x, y; t) \mapsto (\alpha x, \alpha^{-1} y; t)$, for some $\alpha \neq 1$.

Then it is clear on $C'$, there is no new fixed points, we are done in this case.

- $G_P$ exchanges the two branches (this also implies $2||G_P||$), the action on the family is given by

$\gamma_P : (x, y; t) \mapsto (\alpha y, \alpha^{-1} x, t)$.

We find two new fixed points on $C'$: $Q_1 = (\alpha y_0, y_0)$ and $Q_2 = (-\alpha y_0, -y_0)$, where $y_0$ satisfies $\alpha y_0^2 = t_0$. Then $u = y - y_0$ is a local parameter near $Q_1$, the action of $\gamma$ sends

$u \mapsto \frac{t_0}{\alpha(y_0 + u)} - y_0 = -u \left(1 - \frac{u}{y_0} + \frac{u^2}{y_0^2} - \cdots \right)$.

We see the monodromy of $\gamma_P$ at $Q_1$ is $-1$, a similar computation shows this holds also for $Q_2$.

Combining the above arguments, we see that $[\mathcal{D}(C', G, \rho')]$ is completely determined by $[\mathcal{D}(C, G, \rho)]$.

Hence we only need to consider the strata of $G$-equivariantly non-smoothable curves. In the rest of the article, we do only consider strata whose general curve is $G$-equivariantly non-smoothable.

We first recall some results on Teichmüller space of smooth curves. Given a smooth $H$-marked curve $(C, H, \rho)$, there is an induced map $\tilde{\rho} : H \to \text{Map}_g$ (cf. [3, Section 2]), which induces an $H$-action on $T_g$. $\text{Fix}(H)$ is an
irreducible analytic subset of \( T_g \), whose image inside \( \mathcal{M}_g \) equals \( \mathcal{M}_{g,H,\rho} \).

Set \( G(H) = \bigcap_{C \in \text{Fix}(H)} \text{Stab}_C, (\text{Aut}(C) \simeq \text{Stab}_C \subset \text{Map}_g) \), a general curve in \( \text{Fix}(H) \) has automorphism group \( G(H) \) (cf. [3, Appendix B]). Since both \( T_{g,H,\rho} \) and \( \text{Fix}(H) \) maps finitely onto \( \mathcal{M}_{g,H,\rho} \), a general curve in \( T_{g,H,\rho} \) has the same property as the one in \( \text{Fix}(H) \). Therefore, given a subgroup \( H' \) of a general curve \( C \) in \( T_{g,H,\rho} \), which induces an \( H' \)-marked curve \( (C, H', \rho'') \), \( H' \) can be considered as a subgroup of general curves in \( T_{g,H,\rho} \), which induce the same numerical type as \( (C, H', \rho'') \), this implies that \( \mathcal{M}_{g,H,\rho} \subset \mathcal{M}_{g,H',\rho''} \).

Given a \( G \)-marked stable curve \( (C, G, \rho) \), write

\[
C = \sum_i C_i = \sum_{\lambda \in \Lambda} \sum_{t=1}^{s_{\lambda}} C_{\lambda,t},
\]

where \( \Lambda \) is the index set of isomorphism classes of the irreducible components with marked points \( (C_i, N_i^{(1)}, N_i^{(2)}) \) and \( s_{\lambda} \) is the number of curves \( (C_i, N_i^{(1)}, N_i^{(2)}) \) belonging to the isomorphism class \( \lambda \).

Clearly \( \text{Aut}(C) \) is a subgroup of \( \prod_{\lambda \in \Lambda} ((\prod_{t=1}^{s_{\lambda}} \text{Aut}(C_{\lambda,t})) \rtimes \mathfrak{S}_{s_{\lambda}}) \) consisting of elements preserving the nodes of \( C \), where for each class \( \lambda \) we fix an identification of \( \text{Aut}(C_{\lambda,t}) \) for all curves \( C_{\lambda,t} \) and the semi-direct product is determined by the following group homomorphism:

\[
\mathfrak{S}_{s_{\lambda}} \longrightarrow \text{Aut} \left( \prod_{t=1}^{s_{\lambda}} \text{Aut}(C_{\lambda,t}) \right), \sigma \mapsto \phi_{\sigma} : (g_1, \ldots, g_{s_{\lambda}}) \mapsto (g_{\sigma(1)}, \ldots, g_{\sigma(s_{\lambda})}).
\]

Now assume \( C \) is a general curve of a stratum, and \( D \) is another curve inside the same stratum. Applying the previous mentioned results on smooth curves to the components of \( C \) and \( D \), we may identify \( \prod_{\lambda \in \Lambda} ((\prod_{t=1}^{s_{\lambda}} \text{Aut}(C_{\lambda,t})) \rtimes \mathfrak{S}_{s_{\lambda}}) \) with \( \prod_{\lambda \in \Lambda} ((\prod_{t=1}^{s_{\lambda}} \text{Aut}(D_{\lambda,t})) \rtimes \mathfrak{S}_{s_{\lambda}}) \) and consider \( \text{Aut}(C), \text{Aut}(D) \) as subgroups. For an element \( (g_{\lambda,t}, \sigma_{\lambda}) \in \text{Aut}(C) \), each \( g_{\lambda,t} \) corresponds to a \( g'_{\lambda,t} \in \text{Aut}(D_t) \), such that the numerical type induced by \( g'_{\lambda,t} \) is the same as that of \( g_{\lambda,t} \), hence \( \{g'_{\lambda,t}\} \) satisfy the compatibility condition and yields an element \( (g'_{\lambda,t}, \sigma_{\lambda}) \in \text{Aut}(D) \), moreover, the numerical type of \( (g_{\lambda,t}, \sigma_{\lambda}) \) and \( (g'_{\lambda,t}, \sigma_{\lambda}) \) are the same.

In fact, we have deduced the following proposition:

**Proposition 3.2.**

1. Given a stratum, the automorphism groups of general curves in the stratum remain the same, hence we define the automorphism group of a stratum to be the automorphism group of a general curve inside the stratum.
Let $G'$ be the automorphism group of a stratum $\mathcal{M}_{[D(C,G,\rho)]}$, for any cyclic subgroup $H$ of $G'$, the induced $H$-numerical types on general curves are identical, say $[D(C', H, \rho')]$, this means there is an open subset $U$ of $\mathcal{M}_{[D(C,G,\rho)]}$ with $U \subset \mathcal{M}_{[D(C', H, \rho')]}$.

**Definition 3.3.** — Given a stratum, we say that (the action of) $G$ is maximal if for any general curve $(C, G, \rho)$ inside the stratum, there is no subgroup $G' \subset \text{Aut}(C)$ isomorphic to $G$ (including $G$ itself) such that the induced $G'$-marked stable curve $(C, G')$ is $G'$-equivariantly smoothable or the dimension of the stratum corresponding to $(C, G')$ is larger than the dimension of the given one.

**Remark 3.4.** — Let $\mathcal{M}_{[D(C,G,\rho)]}$ and $\mathcal{M}_{[D(C',G,\rho')]})$ be two strata whose general curves are $G$-equivariantly non-smoothable. If $\mathcal{M}_{[D(C,G,\rho)]} \subset \mathcal{M}_{[D(C',G,\rho')]})$, we have two cases:

1. If there is a general curve $[C] \in \mathcal{M}_{[D(C,G,\rho)]}$ such that $[C] \in \mathcal{M}_{[D(C',G,\rho')]})$, then this means there is a subgroup $G'$ of $\text{Aut}(C)$ isomorphic to $G$, such that the induced $G'$-numerical type is exactly $[D(C, G, \rho)]$, by Proposition 3.2(2), there is an open subset $U$ of $\mathcal{M}_{[D(C,G,\rho)]}$ such that $U \subset \mathcal{M}_{[D(C',G,\rho')]})$.

2. If no general curve in $\mathcal{M}_{[D(C,G,\rho)]}$ is contained in $\mathcal{M}_{[D(C',G,\rho')]})$, since $(C, G, \rho)$ is $G$-equivariantly non-smoothable, the only possibility is that there is a subgroup $G'$ of $\text{Aut}(C)$ isomorphic to $G$, such that the induced $G'$-marked curve $(C, G' \simeq G, \rho')$ can be $G$-equivariantly deformed to a $G$-marked stable curve with numerical type $[D(C', G, \rho')]$.

Hence we see that the notion of maximal $G$-action is enough to determine the maximal strata (although a maximal stratum may correspond to more than one numerical type).

Once we know the automorphism group of the stratum, we can find the subgroups which are isomorphic to $G$ and hence determine whether the stratum is maximal.

Now for fixed genus $g$ and group $G$, we can determine the irreducible components (equivalently, the maximal strata) of $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$ since the possible configurations are finite. However if we do not fix the genus $g$, due to the following phenomena, it is not so easy to obtain a brief description of the irreducible components even for cyclic groups.

Recall that in the smooth case a stratum with group $G$ is called full if the automorphism group of the stratum equals $G$. Now for a $G$-marked stable
curve \((C = \sum_i C_i, G, \rho)\), if for some \(i\), the group \(H_i\) is not full for the induced action of \(H_i\) on \(C_i\), the complicity of \(\text{Aut}(C)\) increases.

We give an example for the automorphism group of a non-full stratum of smooth curves. By [8, Lemma 4.1] we know that for a general smooth curve \(C\) inside a non-full stratum, \(G\) is a normal subgroup of \(\text{Aut}(C)\) and \(\text{Aut}(C)/G\) is isomorphic to \(\mathbb{Z}/2\mathbb{Z}\), \((\mathbb{Z}/2\mathbb{Z})^2\), etc. In the case of \(G\) being cyclic and \(\text{Aut}(C)/G \simeq (\mathbb{Z}/2\mathbb{Z})^2\), by [8, Lemma 4.1] there are three elements \(b_1, b_2, b_3 \in \text{Aut}(C) - G\), such that \(b_i\) has order 2 and the product \(b_1b_2b_3\) is contained in \(G\). The following proposition tells us in this case all the possibilities for \(\text{Aut}(G)\): ([6, Lemma 5.7])

**Proposition 3.5.** — Let \(G(H)\) be a group containing a normal cyclic subgroup \(H\) of order \(d\) such that \(G(H)/H \simeq (\mathbb{Z}/2\mathbb{Z})^2\). Assume in addition that there exist three elements \(b_1, b_2, b_3 \in G(H) - H\) such that \(b_i\) has order 2 and the product \(b_1b_2b_3\) is contained in \(H\). Then \(G(H)\) has the presentation:

\[
\{\alpha, \beta_1, \beta_2 | \alpha^d = 1, \beta_1^2 = \beta_2^2 = 1, \beta_1 \alpha = \alpha^l \beta_1, \beta_2 \alpha = \alpha^z \beta_2, \beta_1 \beta_2 = \beta_2 \beta_1 \alpha^{e_{1,2}}\}
\]

such that \(0 \leq l_1, l_2, e_{1,2} < d\), \(\gcd(l_i, d) = 1\), \(l_i^2 \equiv 1 \bmod d\), \(d|(l_i + 1)e_{1,2}\), for \(i = 1, 2\) and \(\gcd(d, l_1l_2 + 1)|e_{1,2}\).

Moreover, \(\gamma := \bar{\alpha}\) is a generator of \(H\); \(b_i = \bar{\beta_i}\), \(b_i \gamma b_i = \gamma^{l_i}\) for \(i = 1, 2\) and \(b_2b_1b_2 = b_1 \gamma^{e_{1,2}}\), \(b_3 = b_1b_2 \gamma^f\), where \(f\) is an integer such that \(0 \leq f < d\) and \(d|((l_1l_2 + 1)f + e_{1,2})\).

In the smooth case, in order to determine if a stratum is maximal, we only need to compute the subgroups of \(G(H)\) which are isomorphic to \(H\). However, for stable curves, we have to compute all the cyclic subgroups of \(\text{Aut}(\tilde{C}_i)\) and solve a combinatoric problem concerning the dual graph and all the cyclic subgroups of \(\text{Aut}(\tilde{C}_i)\) for each \(C_i\).

In order to have a more detailed discussion, for the rest of the article we make the following assumptions:

**Assumption 3.6.**

(0) \((C = \sum_{i \in I} C_i, G, \rho)\) is \(G\)-equivariantly non-smoothable.\(^{(1)}\)

(1) For a general stable curve \((C, G, \rho)\) in the stratum we have \(H_i = \text{Aut}(\tilde{C}_i)\) and \(g(\tilde{C}_i) \geq 2\) for all \(i\).

(2) For any \(i \in I\), the parameterizing space \(T_{h_i, r_i}\) has dimension > 0.

\(^{(1)}\)Of course, this is a necessary condition for having a maximal stratum by Remark 3.1.
Remark 3.7.

(1) By assumption (2), for a general curve \((C,G,\rho)\) in the stratum, two irreducible components coming from different \(G\)-orbits must be non-isomorphic, hence we have \(\text{Orb} = \Lambda\). Therefore any \(\beta \in \text{Aut}(C)\) fixes the \(G\)-orbits and induces \(\beta_o := \beta|_{C(o)} \in \text{Aut}(C(o))\), conversely \((\beta_o)_{o \in \text{Orb}}\) determines \(\beta\).

(2) Given \(\beta = (\beta_o) \in \text{Aut}(C)\), the order of \(\beta\) is \(\text{lcm}\{\text{Ord}(\beta_o)\}\). Using the isomorphism in Lemma 2.10 and regarding \(\beta_o\) as an element in \((\prod_{j=1}^{n_o} \text{Aut}(C_o^{(j)})) \times \mathfrak{S}_{n_o}\), we can write \(\beta_o = ((\beta_{o,1}, \ldots, \beta_{o,n_o}), \overline{\beta_o})\).

What is the order of \(\beta_o\)? Assume that \(\overline{\beta_o}\) has \(\mu_o(\beta)\) orbits in \(o\) with lengths \(l_1, \ldots, l_{\mu_o(\beta)}\), then we have

\[
\overline{\beta_o} = (i_1, \ldots, i_{l_1})(i_{l_1}+1, \ldots, i_{l_1+l_2})\ldots(i_{n_o-l_{\mu_o(\beta)}+1}, \ldots, i_{n_o})
\]

and

\[
\text{Ord}(\beta_o) = \text{lcm}\left(\text{Ord}(\beta_{o,i_1} \ldots \beta_{o,i_{l_1}})l_1, \ldots, \text{Ord}(\beta_{o,i_{n_o-l_{\mu_o(\beta)}+1}} \ldots \beta_{o,i_{n_o}})l_{\mu_o(\beta)}\right).
\]

We want to understand when the stratum is maximal. For this purpose we study first quotient curves of type \(C/\langle \beta \rangle\), where \(\beta \in \text{Aut}(C) - G\) is an element of order \(d\).

Lemma 3.8. — For any \(\beta \in \text{Aut}(C)\), the quotient map \(\pi : C \to C' := C/G\) factors through the quotient map \(C \to C/\langle \beta \rangle\).

Proof. — Note that we have the following decomposition of \(C'\) into irreducible components: \(C' = \sum_{o \in \text{Orb}} C'_o\). (2)

For the lemma, it suffices to show that for any \(P \in C\), \(\pi(P) = \pi(\beta(P))\). By assumption (2) we have that \(\beta(C(o)) = C(o)\), therefore it suffices to consider the map \(\pi|_{C(o)} : C(o) \to C'_o\) and \(\beta_o := \beta|_{C(o)}\). Using Lemma 2.10 we see this is equivalent to considering the map \(\pi_o : \bigcup_{j=1}^{n_o} C_o^{(j)} \to C'_o\), where \(\pi_o\) is the composition of \(\pi|_{C(o)}\) with the natural map \(\bigcup_{j=1}^{n_o} C_o^{(j)} \to C(o)\).

We determine first the fibre of \(\pi_o\): noting that \(\tilde{\gamma}\) acts transitively on the vertices inside \(o\), hence any fibre of \(\pi_o\) must contain at least a point in \(C_o^{(1)}\), say \(x^{(1)} \in C_o^{(1)}\). Here we only discuss in detail the case where \(x^{(1)}\) does not lie in the inverse image of a node of \(C(o)\), the other case is similar. Then using the isomorphism of Lemma 2.10 we see that \(\pi_o^{-1}(\pi_o(x^{(1)})) = \{x^{(1)}, \gamma^{n_o}(x^{(1)}), \ldots, \gamma^{n_o'-n_o}(x^{(1)}); x^{(2)}, \ldots, \gamma^{n_o'-n_o}(x^{(2)}); \ldots; x^{(n_o)}; \gamma^{n_o'-n_o}(x^{(n_o)})\}\), where \(n_o' := d/[G'_i]\) for any \(i \in o\) and \(x^{(j)}\).

(2) For any \(i \in o\), \(\tilde{C}'_i = \text{normalization of } C'_o\).
denotes the point on \(C_o^{(j)}\) which equals to \(x^{(1)}\) via the identification \(C_o^{(j)} = C_o^{(1)}\). Now since \(\beta_o = ((\beta_{o,1}, \ldots, \beta_{o,n_o}); \overline{\beta}_o)\) and \(\forall x^{(j)} \in C_o^{(j)}, \beta_o(x^{(j)}) = \beta_{o,\overline{\beta}_o(j)}(\overline{\beta}_o(j))\), by assumption (1) we have that \(\beta_{o,\overline{\beta}_o(j)} \in \langle \gamma^{n_o} \rangle\) and hence \(\beta_o(x^{(j)}) \in \pi_o^{-1}(\pi_o(x^{(1)}))\).

Remark 3.9. — For simplicity we denote by \(\mathcal{M}_{C'}\) the stratum corresponding to \(C \to C'\) and by \(\mathcal{M}_\beta\) the stratum corresponding to \(C \to C/\langle \beta \rangle\) (similarly for \(\mathcal{T}_{C'}\) and \(\mathcal{T}_\beta\)), Lemma 3.8 says that an open subset \(U\) of \(\mathcal{M}_{C'}\) is contained in \(\mathcal{M}_\beta\) (not just in \(\mathcal{M}_\beta\)). If \(\mathcal{M}_{C'}\) is not maximal, by Remark 3.4 there are two cases:

1. there exists a \(\beta \in \text{Aut}(C)\) of order \(d\), such that \(\dim \mathcal{M}_\beta > \dim \mathcal{M}_{C'}\);
2. there exists a \(\beta \in \text{Aut}(C)\) of order \(d\), such that \(\dim \mathcal{M}_\beta = \dim \mathcal{M}_{C'}\) and \((C, \beta)\) is \(G\)-equivariantly smoothable.

Recall that \(\mathcal{T}_{C'}\) is the product of the parameterizing spaces of all the coverings \(C(o) \to C'_o\), which is isomorphic to the parameterizing space \(\mathcal{T}_{C'_o}\) of the covering \(C_o^{(1)} \to C'_o\) (strictly speaking, of the covering \(C_o^{(1)} \to \overline{C'_o}\)). Denoting by \((C/\langle \beta \rangle)(o)\) the inverse image of \(C'_o\) in \(C/\langle \beta \rangle\), the number of irreducible components of \((C/\langle \beta \rangle)(o)\) is \(\mu_o(\beta)\). Hence the parameterizing space of \(C(o) \to (C/\beta)(o)\) is a product of \(\mu_o(\beta)\) parameterizing spaces of the irreducible components of \((C/\beta)(o)\), all of which have dimension greater than or equal to \(\dim \mathcal{T}_{C'_o}\). Now we can characterize case (1) of Remark 3.9:

**Lemma 3.10.** — Case (1) of Remark 3.9 happens if and only if \(\exists o \in \text{Orb}\), such that one of the following cases occurs:

a) \(\mu_o(\beta) > 1\);

b) \(\mu_o(\beta) = 1\) and \(3 \text{Ord}(\beta_o^{n_o}) \leq \text{Ord}(H_i)\) for any \(i \in o\);

c) \(\mu_o(\beta) = 1, 2 \text{Ord}(\beta_o^{n_o}) = \text{Ord}(H_i)\) for any \(i \in o\) and we are not in the exceptional cases of Proposition 3.13.

**Proof.** — First note that \(\text{Ord}(H_i)\) does not depend on the choice of \(i \in o\). By assumption (2) \(\dim \mathcal{T}_{C'_o} \geq 1\), hence (a) follows from the preceding discussion. If \(\mu_o(\beta) = 1\) for all \(o\), we have that \(C/\langle \beta \rangle(o)\) is an irreducible curve, in case (b) by Proposition 3.13 we always have \(\dim \mathcal{T}_{C/\langle \beta \rangle(o)} > \dim \mathcal{T}_{C'_o}\); if \(2 \text{Ord}(\beta_o^{n_o}) = \text{Ord}(H_i)\) then \(\dim \mathcal{T}_{C/\langle \beta \rangle(o)} > \dim \mathcal{T}_{C'_o}\) except for the cases in Proposition 3.13. 

Now we discuss briefly the exceptional cases mentioned in 3.10, since the technique we use here is independent of the other part of this paper, we only sketch the proof and for reader who are interested in details we refer to [2, 8, 7]. First we introduce a few settings (cf. [8, Section 2]).
LEMMA 4.1. — Let $C \to C/G =: C'$ be a cyclic cover and $B = \{ P_1, \ldots, P_r \} \subset C'$ the branching locus, then topologically this is determined by a surjective group homomorphism

$$f : \pi_1(C' - B) \to G.$$Fix a set of small circles $\{ \gamma_j \}_{1 \leq j \leq r}$ with each $\gamma_j$ around the point $P_j$, denote by $c_j$ the order of $f(\gamma_j)$ in $G$. We call the (unordered) sequence $(c_1, \ldots, c_r)$ the signature of the $G$-marked curve $C$ (or equivalently, of the $G$-cover $C \to C'$).

**Remark 3.12.** — Under the condition of Definition 3.11, assume that $d = |G|$ and $P_j \in D_{i_j}$. Since $f(\gamma_j) = [i_j]$ (possibly after replacing some $[\gamma_j]$ by $[\gamma_j]^{-1}$), we have $c_j \gcd(d, i_j) = d$.

**Proposition 3.13.** — Given an admissible branching sequence $[(k_1, \ldots, k_{d-1})]$ for $g \geq 2$, assume that $\dim \mathcal{T}_{g; d, [(k_1, \ldots, k_{d-1})]} \geq 1$ and for any general curve $C \in \mathcal{T}_{g; d, [(k_1, \ldots, k_{d-1})]}$, $G = \text{Aut}(C)$. For any proper subgroup $G'$ of $G$, we have an induced cyclic cover of degree $d' := \text{ord}(G') : C \to C/G'$ and hence an admissible sequence $[(k'_1, k'_2, \ldots, k'_{d'-1})]$ for $d'$ and $g$. Then $\dim_C \mathcal{T}_{g; d, [(k_1, \ldots, k_{d-1})]} > \dim_C \mathcal{T}_{g; d', [(k'_1, \ldots, k'_{d'-1})]}$ except for three cases:

1. $d = 2d' \geq 4$, $2 \mid d'$, $C/G \simeq \mathbb{P}^1$, $[(k_1, \ldots, k_{d-1})] = [(1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1)]$ and $[(k'_1, \ldots, k'_{d'-1})] = [(1, 0, \ldots, 0, k_{d'/2} = 2, 0, \ldots, 0, 1)];$
2. $d = 2d' \geq 6$, $2 \not\mid d'$, $C/G \simeq \mathbb{P}^1$, $[(k_1, \ldots, k_{d-1})] = [(0, 1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1, 0)]$ and $[(k'_1, \ldots, k'_{d'-1})] = [(1, 0, \ldots, 0, 1)];$
3. $d = 2$, $g(C) = 2$, $C/G \simeq \mathbb{P}^1$, $[(k_1)] = [(6)].$

**Proof.** — If $\dim_C \mathcal{T}_{g; d, [(k_1, \ldots, k_{d-1})]} = \dim_C \mathcal{T}_{g; d', [(k'_1, \ldots, k'_{d'-1})]}$, then we have that $\mathcal{T}_{g; d, [(k_1, \ldots, k_{d-1})]} = \mathcal{T}_{g; d', [(k'_1, \ldots, k'_{d'-1})]}$. Now since the condition of [8, Lemma 4.1], is satisfied, we see that the pair $(C, G')$ must be one of the cases there.

By assumption $\dim_C \mathcal{T}_{g; d', [(k'_1, \ldots, k'_{d'-1})]} \geq 1$, hence only the cases I, II, III in [8, Lemma 4.1] may happen. Note that in [8, Lemma 4.1], indices of signatures satisfy $c_j \leq c_{j+1}$.

Case III-c is excluded since here $\text{Aut}(C)$ is a cyclic group, which can not have a quotient group isomorphic to $(\mathbb{Z}/2)^2$.

For the remaining cases, we have $d = 2d'$ and $C/\text{Aut}(C) \simeq \mathbb{P}^1$. We now treat the cases separately, for a branching point $P_j \in \mathbb{P}^1$, denote by $i_j$ the index satisfying $P_j \in D_{i_j}$.

**Case I.** — The covering map has 6 branching points $P_1, \ldots, P_6$ with signature $(2, 2, 2, 2, 2, 2)$. By Remark 3.12 we get $i_j = d'$ for all $1 \leq j \leq 6$, Definition 2.2(1) is automatically satisfied, and 2.2(2) implies $d' = 1$, i.e.,
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\[ G \simeq \mathbb{Z}/2\mathbb{Z} \]. Then by Riemann–Hurwitz formula we see that \( g = 2 \) and the branching sequence is (6).

**Case II.** — The covering map has 5 branching points \( P_1, \ldots, P_5 \) with signature \((2, 2, 2, 2, c_5) (c_5 \geq 2)\). This implies \( i_j = d' \) for \( 1 \leq j \leq 4 \), by 2.2(1) we must have \( d|i_5 \), which is impossible, since by definition we have \( 1 \leq i_5 \leq d - 1 \).

**Cases III-a.** — \( C \to C/G \) has 4 branching points \((P_1, P_2, P_3, P_4)\) with signature \((2, 2, 2, c_4) (c_4 \geq 3 \text{ since we assume } g \geq 2)\), this implies \( i_1 = i_2 = i_3 = d' \) and \((i_4, d) = d/c_4\). Now if Definition 2.2(1) is satisfied, we must have \( i_4 = d' \), then Definition 2.2(2) implies \( d' = 1 \) and \( d = 2 \), which contradicts the fact \( d \geq c_4 \geq 3 \).

**Case III-b.** — \( C \to C/\text{Aut}(C) \) has four branching points \( P_1, P_2, P_3, P_4 \) with signature \((2, 2, c_3, c_4) \) such that \( 2 < c_3 < c_4 \) (since we assume \( g \geq 2 \)). Using Remark 3.12, we get \( i_1 = i_2 = d' \), \( c_3 = d/\gcd(d, i_3) \) and \( c_4 = d/\gcd(d, i_4) \), since \( 2 < c_3 < c_4 \), we have \( i_3, i_4 \neq d' \) and \( d \geq c_3 > 2 \). Moreover Definition 2.2(1) says that \( d|(d' + d' + i_3 + i_4) \), which implies that \( d|(i_3 + i_4) \); 2.2(2) says that \( \gcd(d, d', i_3, i_4) = 1 \), which is equivalent to \( \gcd(d', i_3) = 1 \). Therefore we have \( \gcd(d, i_3) = 1 \) or \( 2 \), where the \( = 2 \) case happens only if \( 2 \nmid d' \). Since we are interested in the equivalent class of branching sequences, after possibly a change of generator of \( G \), the above numerical restriction on \( \{i_3, i_4\} \) yields two possibilities:

\[
\{i_3, i_4\} = \{1, d - 1\} \text{ and } [(k_1, \ldots, k_{d-1})] = [(1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1)]
\]
or

\[
2 \nmid d', \{i_3, i_4\} = \{2, d - 2\},
\]

\[
[(k_1, \ldots, k_{d-1})] = [(0, 1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1, 0)].
\]

Noting that there is one more restriction in case III-b that \( C/G' \to \mathbb{P}^1 \) is a double cover branched in two points on \( \mathbb{P}^1 \), we see that if

\[
[(k_1, \ldots, k_{d-1})] = [(1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1)],
\]

then we must have \( 2|d' \), otherwise \( C/G' \to \mathbb{P}^1 \) is branched on four points on \( \mathbb{P}^1 \); in this case

\[
[(k'_1, \ldots, k'_{d'-1})] = [(1, 0, \ldots, 0, k_{d'/2} = 2, 0, \ldots, 0, 1)].
\]

For the other case where \( 2 \nmid d' \) and

\[
[(k_1, \ldots, k_{d-1})] = [(0, 1, 0, \ldots, 0, k_{d'} = 2, 0, \ldots, 0, 1, 0)],
\]

we get \( [(k'_1, \ldots, k'_{d'-1})] = [(1, 0, \ldots, 0, 1)] \).
Remark 3.14. — Let us look at the case when \( \dim \mathcal{T}_\beta = \dim \mathcal{T}_{C'} \): first \( \mu_o(\beta) = 1 \) for all \( o \in \text{Orb} \), which means that \( \overline{\beta}_o \) acts transitively on the vertices in \( o \).

For the subcurve \( C/(\beta)(o) \), if we are not in the exceptional cases, then we have \( (C/(\beta)(o)) \simeq C'_o \) and \( \beta^n_o|_{C'_o(1)} = \prod_{k=1}^{n_o} \beta_{o,k} \) is a generator of \( \text{Aut}(C'_o(1)) \). Otherwise \( C'_o \) is rational and \( C/(\beta)(o) \to C'_o \) is a double cover and \( \langle \prod_{k=1}^{n_o} \beta_{o,k} \rangle \) is the (unique) index 2 subgroup of \( \text{Aut}(C'_o(1)) \) which arises from the exceptional cases in Proposition 3.13.

We assume to be in one of the above cases, that is under the condition \( \dim \mathcal{T}_\beta = \dim \mathcal{T}_{C'} \), and determine when \( (C, \beta) \) is \( G \)-equivariantly non-smoothable. Here we apply Proposition 2.6 to a node \( p \in \mathcal{N}_{i_1} \cap \mathcal{N}_{i_2} \). We have two cases: \( i_1 = i_2 = i \), \( p \in \mathcal{N}_{i}^{(2)} \) and \( i_1 \neq i_2, p \in \mathcal{N}_{i_1}^{(1)} \cap \mathcal{N}_{i_2}^{(1)} \), which we treat separately.

Case (I). — If \( p \in \mathcal{N}_{i}^{(2)} \), we must have \( G_p \subset G_i \). Denoting by \( \{p_1, p_2\} \) the inverse image of \( p \) of the normalization map \( \tilde{C}_i \to C_i \), we have the following easy lemma:

Lemma 3.15. — For any \( g \in H_i \), (regarding \( g \) also as an automorphism of \( \tilde{C}_i \) ) there are three possibilities:

(a) \( g(p_i) = p_i \) for \( i = 1, 2 \).
(b) \( g(p_1) = p_2 \) and \( g(p_2) = p_1 \).
(c) \( g(p_1) = p'_1 \) and \( g(p_2) = p'_2 \), where \( \{p'_1, p'_2\} \) is the inverse image of \( g(p)(\neq p) \).

Proof. — Obvious. \( \square \)

We apply Proposition 2.6 to \( (C_i, H_i = \langle \gamma^n_i |_{C_i} \rangle \) and \( (C_i, \langle \overline{\beta}^n_i |_{C_i} \rangle \). If \( \langle \overline{\beta}^n_i |_{C_i} \rangle = H_i \), then by assumption (0) it is clear that \( p \) is non-smoothable for \( (C_i, \langle \overline{\beta}^n_i |_{C_i} \rangle \) and hence non-smoothable for \( (C, \langle \beta \rangle) \).

Assume we are in the exceptional cases of Proposition 3.13. First we consider exceptional case (1), recall that \( \pi_i : \tilde{C}_i \to \tilde{C}_i/H_i \) is branched on four points \( P_1, \ldots, P_4 \) with signature \( (2, 2, d_i, d_i) \) with \( d_i \geq 4 \). Note that \( p_1 \) or \( p_2 \) does not belong to either \( \pi_i^{-1}(P_1) \) or \( \pi_i^{-1}(P_2) \):

Case (a) in Lemma 3.15 does not occur since \( \#\pi_i^{-1}(P_1) = \#\pi_i^{-1}(P_2) = d_i/2 \geq 2 \).

For the same reason, if \( d_i \geq 6 \), then Case (b) does not occur; if \( d_i = 4 \), Case (b) does not occur, either, otherwise \( p \) is \( H_i \)-equivariantly smoothable.
Case (c) does not occur, otherwise $p$ is $H_i$-equivariantly smoothable.

Hence we may assume $p_1 = \pi_i^{-1}(P_3)$ and $p_2 = \pi_i^{-1}(P_4)$. Let $z_j$ be a local coordinate near $p_j$, $j=1,2$, the action of $H_i$ near $p$ is
\[ \gamma_i^n : z_1 \mapsto \zeta d, z_2 \mapsto \zeta d^{-1} z_2. \]
This implies that $p$ is $H_i$-equivariantly smoothable, a contradiction. Therefore we see that exceptional case (1) does not occur.

Using a similar argument we see that exceptional cases (2) and (3) do not occur, either.

Case (II): $i_1 \neq i_2, p \in \mathcal{N}_{i_1} \cap \mathcal{N}_{i_2}$. — We have two subcases:

(i) $G_p$ fixes $i_1$ and $i_2$ respectively.
(ii) $G_p$ exchanges $i_1$ with $i_2$.

Subcase (i). — Let $x$ (resp. $y$) be a local parameter on $C_{i_1}$ (resp. on $C_{i_2}$) near $p$. Denoting by $a_l$ the smallest positive integer such that $\gamma_l n_{i_1} a_l(p) = p$ for $l = 1, 2$ (note that we necessarily have $n_{i_1} a_1 = n_{i_2} a_2$), then locally the action of $\gamma_l n_{i_1}$ around $p$ is given by $(x, y) \mapsto (b_1 x, b_2 y)$ for some natural numbers $b_1, b_2$, where $\zeta_{p,l}$ is a primitive $n_{i_1}$-th root of unity and $n_{i_1} : d = |G_{i_1}|$ (we require that $b_1, b_2 \leq n_{i_1}$). The condition that $(C, G, \rho)$ is non-smoothable implies that $\zeta_{p,1}^{b_1} \zeta_{p,2}^{b_2} \neq 1$.

By our assumption (1) we have $\beta n_{i_1} \mid C_{i_1} \in \text{Aut}(C_{i_1}) = \langle \gamma_l n_{i_1} \mid C_{i_1} \rangle$, hence we get that $\beta n_{i_1} \mid C_{i_1} = (\gamma_l n_{i_1})^{c_l}$ for some $0 \leq c_l < \text{Ord}(H_{i_1})$. By Proposition 3.13 we have two possibilities:

- $\langle \beta n_{i_1} \mid C_{i_1} \rangle = \text{Aut}(C_{i_1})$, which is equivalent to $\text{gcd}(c_l, \text{Ord}(H_{i_1})) = 1$.
- We are in the exceptional cases where $\langle \beta n_{i_1} \mid C_{i_1} \rangle$ is the index 2 subgroup of $\text{Aut}(C_{i_1})$, and $c_l = 2 c_l'$ for some $0 \leq c_l' < \text{Ord}(H_{i_1})/2$ with $\text{gcd}(c_l', \text{Ord}(H_{i_1})) = 1$.

The action of $\beta n_{i_1}$ is given by $(x, y) \mapsto (b_1 x, b_2 y, b_2 c_2 y)$. We see easily that $p$ is non-smoothable for $(C, \langle \beta n_{i_1} \mid C_{i_1} \rangle)$ iff $\zeta_{p,1}^{b_1 c_1} \zeta_{p,2}^{b_2 c_2} \neq 1$.

Subcase (ii). — Observe that $i_1$ and $i_2$ lie in the same orbit, hence we have $d_{i_1} = d_{i_2}$ and we may identify $H_{i_1}$ with $H_{i_2}$. For any element in $H_{i_1}$ fixing the node $p$, the induced monodromies on two branches of $p$ are the same.

First we deduce a restriction on $l_{p,i_1}$, the length of the $G_{i_1}$-orbit of $p$. Assume $G_p = \langle \gamma^n \rangle$ for some $a \mid d$ and consider the group $K_{p,i_1} := G_p \cap G_{i_1} = \langle \gamma^b \rangle$ for some $b \mid d$, which is the subgroup of $G$ simultaneously fixing $p$ and leaving $C_{i_1}$ invariant. Regarding $K_{p,i_1}$ as a subgroup of $G_p$, we should have
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\( b = 2a; \) on the other hand regarding \( K_{p,i} \) as a subgroup of \( G_{i} \), we have \( b = n_{i} l_{p,i} \). Hence we have \( 2a = n_{i} l_{p,i} \). If \( 2|l_{p,i} \), we see that \( n_{i} a \), which is absurd since in subcase (ii) \( G_{p} \) is not contained in \( G_{i} \), therefore \( l_{p,i} \) must be an odd number.

If \( \langle n_{i}^{l_{p,i}} | C_{i} \rangle = H_{i} \), then the same holds for \( C_{i} \) and for \( G_{p} \). For the same reason as in case (I), \( p \) is non-smoothable for \( (C, \langle \beta \rangle) \).

Now we consider the exceptional cases, where \( \langle n_{i}^{l_{p,i}} | C_{i} \rangle \subset H_{i} \) is the unique index 2 subgroup of \( H_{i} \) (the same for \( C_{i} \)), let \( x \) (resp. \( y \)) be a local parameter on \( C_{i} \) (resp. on \( C_{i} \)) near \( p \).

We discuss according to the monodromy of \( H_{i} \) at the node \( p \), there are two cases:

(a) The monodromy order is greater than or equal to 3, including the ramification points over \( P_{3}, P_{4} \) in the exceptional cases (1) (the case of ramification points over \( P_{3}, P_{4} \) in the exceptional cases (2) does not occur because there \( P_{3} \) or \( P_{4} \) has inverse images of even length), locally the action of \( G_{p} = \langle \gamma_{a} \rangle \) is \( \gamma_{a} : (x,y) \mapsto (\zeta_{d_{i}^{2}} y, x) \), the action corresponding to \( \langle n_{i}^{l_{p,i}} \rangle \) is then \( (x,y) \mapsto (\zeta_{d_{i}^{2}}^{2} y, x) \). Since in the exceptional case (1) \( d_{i} \geq 4 \), we see that \( p \) is non-smoothable.

(b) The monodromy order equals 2, and the length of the \( H_{i} \)-orbit of \( p \) is an odd number. This includes the following:
   - exceptional case (2), \( p \) is a ramification point over \( P_{1} \) or \( P_{2} \).
     (note that in exceptional case (1), \( d' \) is even, hence the case that \( p \) is a ramification point over \( P_{1}, P_{2} \) of exceptional case (1) does not occur.)
   - exceptional case (3), \( p \) is a ramification point.

With a similar argument as in (a), we see that \( p \) is smoothable.

**Definition 3.16.** — We say a node \( p \) is of type \( E \) with respect to \( \beta \in \text{Aut}(C) \), if it is in the case of (b) above.

Now we fix the local parameters for each nodes where subcase (II-i) happens, then we obtain an unordered pair \( (\zeta_{p,1}^{b(p,1)}, \zeta_{p,2}^{b(p,2)}) \) at each node \( p \) which is determined by \( \gamma \). For any \( \beta \in \text{Aut}(C) \) with degree \( d \) such that \( \dim T_{\beta} = \dim T_{C^{'}} \), we get a pair of integers \( (c(\beta,p,1), c(\beta,p,2)) \) at each node.

Combining with the previous argument, we obtain our main theorem:
Theorem 3.17. — Under the conditions of Assumption 3.6, we have the following:

(1) For a $G$-equivariantly non-smoothable $G$-marked stable curve $(C = \sum_{i \in I} C_i, G, \rho)$, the induced stratum $\mathcal{M}_{C'}$, where $C' = C/G$, is maximal iff for a general stable curve (by abuse of notation we denote still by) $(C, G, \rho)$ in the stratum:

(a) The cases in Lemma 3.10 do not occur.
(b) For any $\beta \in \text{Aut}(C)$ (of order $d$) and any node $p$ where Case (II-i) happens, the following holds:
$$\zeta_p^{b(p,1)c(\beta,p,1)} \neq 1.$$
(c) For any $\beta \in \text{Aut}(C)$ (of order $d$), there is no node $p$ of type $E$ with respect to $\beta$.

(2) The Zariski closure of each maximal stratum in (1) is an irreducible component of $(\overline{\mathcal{M}}_g - \mathcal{M}_g)(G)$.

Remark 3.18. — The above argument also shows that, unlike in the smooth case (cf. [4, Theorem 1] and [1, Theorem 3.4]), for stable curves, usually a component corresponds to more than one numerical types.

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Bibliography

[1] F. Catanese, “Irreducibility of the space of cyclic covers of algebraic curves of fixed numerical type and the irreducible components of $\text{Sing}(\overline{\mathcal{M}}_g)$”, in Advances in geometric analysis, Advanced Lectures in Mathematics (ALM), vol. 21, International Press, 2012, p. 281-306.
[2] F. Catanese, M. Lönne & F. Perroni, “Irreducibility of the space of dihedral covers of algebraic curves of fixed numerical type”, Rend. Lincei Mat. Appl. 22 (2011), p. 291-309.
[3] ———, “The irreducible components of the moduli space of dihedral covers of algebraic curves”, Groups Geom. Dyn. 9 (2015), no. 4, p. 1185-1229.
[4] M. Cornalba, “On the locus of curves with automorphisms”, Ann. Mat. Pura Appl. 149 (1987), p. 135-151.
[5] ———, “Erratum: On the locus of curves with automorphisms”, Ann. Mat. Pura Appl. 187 (2008), no. 1, p. 185-186.
[6] B. Li, “Moduli spaces of varieties with symmetries”, PhD Thesis, University of Bayreuth, 2016, https://epub.uni-bayreuth.de/2970/.
Cyclic covers of Stable curves

[7] B. Li & S. Weigl, “The locus of curves with $D_n$-symmetry inside $\mathcal{M}_g$”, *Rend. Circ. Mat. Palermo (2)* 65 (2016), no. 1, p. 33-45.

[8] K. Magaard, T. Shaska, S. Shpectorov & H. Völklein, “The locus of curves with prescribed automorphism group”, in *Communications in arithmetic fundamental groups (Kyoto, 1999/2001)*, vol. 1267, RIMS Kokyuroku, no. 1267, Research Institute for Mathematical Sciences, 2002, p. 112-141.