Abstract. Let $\text{Mod}_g$ be the mapping class group of a genus $g \geq 2$ surface. The group $\text{Mod}_g$ has virtual cohomological dimension $4g - 5$. In this note we use a theorem of Broaddus and the combinatorics of chord diagrams to prove that $H^{4g-5}(\text{Mod}_g; \mathbb{Q}) = 0$.

1. Introduction

Let $\text{Mod}_g$ be the mapping class group of a closed, oriented, genus $g \geq 2$ surface, and let $\mathcal{M}_g$ be the moduli space of genus $g$ Riemann surfaces. It is well-known that for each $i \geq 0$,

$$H^i(\text{Mod}_g; \mathbb{Q}) \cong H^i(\mathcal{M}_g; \mathbb{Q}).$$

It is a fundamental open problem to determine the maximal $i$ for which these vector spaces are nonzero. Harer [Ha] proved that the virtual cohomological dimension $\text{vcd}(\text{Mod}_g)$ equals $4g - 5$. More precisely, he proved that $H^{4g-5}(\text{Mod}_g; \text{St}_g \otimes \mathbb{Q}) \neq 0$ for a certain $\text{Mod}_g$-module $\text{St}_g$ (see below for details) and that $H^i(\text{Mod}_g; V \otimes \mathbb{Q}) = 0$ for all $i > 4g - 5$ and all $\text{Mod}_g$-modules $V$. Thus the first step of the problem above is to determine whether $H^{4g-5}(\text{Mod}_g; \mathbb{Q}) \neq 0$. The purpose of this note is to answer this question.

Let $\text{Mod}_{g,*}$ (resp. $\text{Mod}_{g,1}$) denote the mapping class group of the genus $g$ surface with one marked point (resp. one boundary component).

**Theorem 1.** For any $g \geq 2$,

$$H^{4g-5}(\text{Mod}_g; \mathbb{Q}) = H^{4g-5}(\mathcal{M}_g; \mathbb{Q}) = 0.$$

Further, the rational cohomology of $\text{Mod}_{g,*}$ (resp. the integral cohomology of $\text{Mod}_{g,1}$) vanishes in its virtual cohomological dimension.

This theorem was announced some years ago by Harer, but he has informed us that his proof will not appear. We recently learned that Morita–Sakasai–Suzuki [MSS] have independently found a proof of Theorem 1 using a completely different method. They apply a theorem of Kontsevich on graph homology to their computation of a generating set for a certain symplectic Lie algebra. Our proof combines some results about the combinatorics of chord diagrams with the work of Broaddus [Br] on the Steinberg module of $\text{Mod}_g$. We thank Allen Hatcher and Takuya Sakasai for their comments on an earlier version of this paper, and John Harer for informing us about the paper [MSS] and his own work.

Theorem 1 is consistent with the well-studied analogy between mapping class groups and arithmetic groups. For example, Theorem 1.3 of Lee–Szczarba [LS] states that the rational cohomology of $\text{SL}(n, \mathbb{Z})$ vanishes in its cohomological dimension.

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The authors gratefully acknowledge support from the National Science Foundation.
2. Background

We begin by briefly summarizing previous results that make our computation possible; for details see Broaddus [Br].

Teichmüller space and its boundary. Let $S_g$ be a connected, closed orientable surface of genus $g \geq 2$. Let $C_g$ be the curve complex of $S_g$ defined by Harvey [Harv], i.e. the flag complex whose $k$-simplices are the $(k+1)$-tuples of distinct free homotopy classes of simple closed curves in $S_g$ that can be realized disjointly. Harer [Ha] proved that $C_g$ is homotopy equivalent to a wedge of spheres $\bigvee_{i=1}^{\infty} S^{2g-2}$.

There exists a constant $\delta > 0$ such that any two closed geodesics on a hyperbolic surface of length $\leq \delta$ are disjoint (the Margulis constant for hyperbolic surfaces). Let $T_g^{thick}$ be the Teichmüller space of marked hyperbolic surfaces diffeomorphic to $S_g$ having no closed geodesic of length $< \delta$. It is known that $T_g^{thick}$ is a $(6g-6)$-dimensional manifold with corners. Ivanov [Iv] proved that $T_{g}^{thick}$ is contractible and that its boundary $\partial T_{g}^{thick}$ is homotopy equivalent to $C_g$. Briefly, for each simplex $\sigma$ of $C_g$, let $T_{\sigma}$ be the subset of $\partial T_{g}^{thick}$ consisting of surfaces where each curve in $\sigma$ has length $\delta$. Each $T_{\sigma}$ is contractible, and $T_{\sigma} \cap T_{\sigma'} = \emptyset$ unless $\sigma \cup \sigma'$ is a simplex of $C_g$, in which case $T_{\sigma} \cap T_{\sigma'} = T_{\sigma \cup \sigma'}$.

Duality in the mapping class group. The mapping class group $\text{Mod}_g$ acts properly discontinuously on $T_{g}^{thick}$ with finite stabilizers. Defining $\mathcal{M}_{g}^{thick} = T_{g}^{thick}/\text{Mod}_g$, it follows that $H^*(\text{Mod}_g; \mathbb{Q}) \cong H^*(\mathcal{M}_{g}^{thick}; \mathbb{Q})$. Mumford’s compactness criterion states that $\mathcal{M}_{g}^{thick}$ is compact. Combining this with the previous two paragraphs, the work of Bieri–Eckmann [BE, Theorem 6.2] shows that $\text{vcd}(\text{Mod}_g) = 4g-5$ and that

\begin{equation}
H^{4g-5}(\text{Mod}_g; \mathbb{Q}) \cong H_0(\text{Mod}_g; H_{2g-2}(C_g; \mathbb{Q})).
\end{equation}

In fact, we can say more. Let $\text{St}_g$ denote the Steinberg module, i.e. the $\text{Mod}_g$-module $H_{2g-2}(C_g; \mathbb{Z})$. Then $\text{St}_g \otimes \mathbb{Q}$ is the rational dualizing module for $\text{Mod}_g$, meaning that

\begin{equation}
H^{4g-5-k}(\text{Mod}_g; M \otimes \mathbb{Q}) \cong H_k(\text{Mod}_g; M \otimes \text{St}_g \otimes \mathbb{Q})
\end{equation}

for any $k$ and any $M$. Moreover $\text{St}_g$ is also the dualizing module for $\text{Mod}_{g,s}$ and $\text{Mod}_{g,1}$, which act on $\text{St}_g$ via the natural surjections $\text{Mod}_{g,s} \to \text{Mod}_g$ and $\text{Mod}_{g,1} \to \text{Mod}_g$ [Ha]. This implies that for $\nu = \text{vcd}(\text{Mod}_{g,s}) = 4g-3$ we have $H^{\nu-k}(\text{Mod}_{g,s}; M \otimes \mathbb{Q}) \cong H_k(\text{Mod}_{g,s}; M \otimes \text{St}_g \otimes \mathbb{Q})$. For $\text{Mod}_{g,1}$ we obtain a similar result with $\nu = \text{cd}(\text{Mod}_{g,1}) = 4g-2$, except that since $\text{Mod}_{g,1}$ is torsion-free the result holds integrally: $H^{\nu-k}(\text{Mod}_{g,1}; M) \cong H_k(\text{Mod}_{g,1}; M \otimes \text{St}_g)$.

An alternate model for $\text{St}_g$. Fix a finite-volume hyperbolic metric on $S_g - \{\ast\}$. Another model for $\text{St}_g$ comes from the arc complex $\mathcal{A}_g$, the flag complex whose $k$-simplices are the disjoint $(k+1)$-tuples of simple geodesics on $S_g - \{\ast\}$ beginning and ending at the cusp $\ast$. Let $\mathcal{A}_g^\infty$ be the subcomplex consisting of collections of geodesics $\gamma_1, \ldots, \gamma_{k+1}$ for which $S - \bigcup \gamma_i$ has some non-contractible component. Harer proved that $\mathcal{A}_g^\infty$ is homotopy equivalent to $C_g$ [Ha], and that $\mathcal{A}_g$ is contractible [Ha2] (see also [Hat]). Thus

\begin{equation}
\text{St}_g = H_{2g-2}(C_g) \simeq H_{2g-2}(\mathcal{A}_g^\infty) \simeq H_{2g-1}(\mathcal{A}_g/\mathcal{A}_g^\infty).
\end{equation}

Chord diagrams. By examining how the geodesics are arranged in a neighborhood of $\ast$, an $(n-1)$-simplex of $\mathcal{A}_g$ can be encoded by a $n$-chord diagram; see [Br, §4.1]. An ordered $n$-chord diagram is an ordered sequence $U = (u_1, \ldots, u_n)$, where $u_i$ iis an unordered pair of distinct points on $S^1$ (a chord) and $u_i \cap u_j = \emptyset$ if $i \neq j$. We will visually depict $U$ by drawing arcs connecting the
points in each \( u_i \) (see Figure 1 for examples). Two ordered chord diagrams are identified if they differ by an orientation-preserving homeomorphism of the circle.

**Filling systems.** An unlabeled \( k \)-filling system of genus \( g \) is a \((2g+k)\)-chord diagram satisfying the conditions described in \([\text{Br}, \S 4.1]\): no chord should be parallel to another chord or to the boundary circle, and the chords should determine exactly \( k+1 \) boundary cycles. These conditions, which guarantee that these chords define a simplex of \( \mathcal{A}_g - \mathcal{A}_g^\infty \), have the following simple combinatorial formulation. Given \( U = (u_1, \ldots, u_n) \), consider two permutations of the \( 2n \) points \( u_1 \cup \cdots \cup u_n \): let \( \omega \) be the \( 2n \)-cycle which takes each point to the point immediately adjacent in the clockwise direction, while \( \tau \) exchanges the two points of each chord \( u_i \) and thus is a product of \( n \) transpositions. Then a \((2g+k)\)-chord diagram is a \( k \)-filling system of genus \( g \) if \( \tau \circ \omega \) has \( k+1 \) orbits, none of which have length 1 or 2. Finally, let \( t_i \) be the straight line in \( D^2 \) connecting the two points of \( u_i \). Then we say that \( U \) is disconnected if the set \( t_1 \cup \cdots \cup t_n \subset D^2 \) is not connected.

**The chord diagram chain complex.** Fix a genus \( g \), and set \( n = 2g+k \). Let \( U_k \) be the free abelian group spanned by ordered \( k \)-filling systems of genus \( g \) modulo the following relation. For \( \sigma \in S_n \) and \( U = (u_1, \ldots, u_n) \), define \( \sigma \cdot U = (u_{\sigma(1)}, \ldots, u_{\sigma(n)}) \). We impose the relation \( \sigma \cdot U = (-1)^{\sigma} U \). The differential \( \partial : U_k \to U_{k-1} \) is defined as follows. Consider an ordered \( k \)-filling system \( U = (u_1, \ldots, u_n) \) of genus \( g \). For \( 1 \leq i \leq n \), let \( \partial_i U = (u_1, \ldots, \hat{u}_i, \ldots, u_n) \) if this is an ordered \((k-1)\)-filling system of genus \( g \); otherwise, let \( \partial_i U = 0 \). Then

\[ \partial(U) = \sum_{i=1}^{n} (-1)^{i-1} \partial_i U. \]

**Broaddus’s results.** We will need the following theorem of Broaddus \([\text{Br}]\). Recall that if \( \Gamma \) is a group and \( M \) is a \( \Gamma \)-module, then the module of coinvariants, denoted \( M_\Gamma \), is the quotient \( M/(g \cdot m - m \mid g \in \Gamma, m \in M) \). Let \( X \) be the 0-filling system of genus \( g \) depicted in Figure 1a.

**Theorem 2** (Broaddus \([\text{Br}]\)). For each \( g \geq 0 \), the following hold.

(i) \( \left( \text{St}_g \right)_{\text{Mod}_g} \cong U_0/\partial(U_1) \).

(ii) The abelian group \( U_0/\partial(U_1) \) is spanned by the image \([X] \in U_0/\partial(U_1)\) of \( X \in U_0 \).

(iii) If \( v \) is a disconnected 0-filling system of genus \( g \), then the image of \( v \) in \( U_0/\partial(U_1) \) is 0.

For part (i) of Theorem 2, see \([\text{Br}, \text{Proposition 3.3}] \) together with the remark preceding \([\text{Br}, \text{Example 4.1}] \); for part (ii), see \([\text{Br}, \text{Theorem 4.2}] \); and for part (iii), see \([\text{Br}, \text{Proposition 4.5}] \).

3. **Proof of Theorem 1**

For any group \( \Gamma \) and any \( \Gamma \)-module \( M \), recall that \( H_0(\Gamma; M) = M_\Gamma \). Since the actions of \( \text{Mod}_{g,*} \) and \( \text{Mod}_{g,1} \) on \( \text{St}_g \) factor through \( \text{Mod}_g \), to prove Theorem 1 it suffices by (1) to show that \( \left( \text{St}_g \right)_{\text{Mod}_g} = 0 \). By Theorem 2(i), this is equivalent to showing that \( U_0/\partial(U_1) = 0 \).

For \( v \in U_0 \), let \([v]\) denote the associated element of \( U_0/\partial(U_1) \). Let \( X = (x_1, \ldots, x_{2g}) \) be the 0-filling system depicted in Figure 1a. By Theorem 2(ii), it is enough to show that \([X] = 0\). Let \( Y = (x_1, \ldots, x_{2g}, y) \) be the 1-filling system depicted in Figure 1b. Observe that

\[ \partial_1 Y = (x_2, \ldots, x_{2g}, y) = (x_1, \ldots, x_{2g}) = X, \]

where the second equality holds since the indicated chord diagrams differ by an orientation preserving homeomorphism of \( S^1 \). Similarly, \( \partial_{2g+1} Y = X \). Also, \( \partial_2 Y = 0 \) (resp. \( \partial_{2g} Y = 0 \)) by definition,
Figure 1. (a) The oriented 0-filling system $X = (x_1, \ldots, x_{2g})$. For concreteness, we depict it for $g = 3$. In general, $X$ has $2g$ chords arranged in the same pattern as the chords shown. (b) The 1-filling system $Y = (x_1, \ldots, x_{2g}, y)$. The chord $y$ intersects the chord $x_{2g}$. (c) The 1-filling system $Z = (z, x_1, \ldots, x_{2g})$. The chord $z$ intersects both $x_1$ and $x_{2g}$.

since the chord $x_1$ (resp. $x_{2g+1}$) becomes parallel to the boundary. We thus have

$$\partial(Y) = 2X + \sum_{i=3}^{2g-1} (-1)^{i-1} \partial_i Y.$$ 

For $3 \leq i \leq 2g - 1$, the 0-filling system $\partial_i Y$ is disconnected, so Theorem 2(iii) implies that $[\partial_i Y] = 0$. We conclude that $2[X] = 0$.

Now consider the 1-filling system $Z = (z, x_1, \ldots, x_{2g})$ depicted in Figure 1(c). Removing any chord from Figure 1(c) yields Figure 1(a) up to rotation, so $\partial_i Z = \pm X$ for each $i$. In fact, it is clear that $\partial_1 Z = X$, that $\partial_2 Z = -X$, that $\partial_3 Z = X$, and so on, with $\partial_i Z = (-1)^{i-1} X$. This shows that

$$\partial(Z) = X + X + \cdots + X = (2g + 1)X,$$

so $(2g + 1)[X] = 0$.

Summing up, we have shown that $2[X] = (2g + 1)[X] = 0$. This implies that $[X] = 0$, as desired.

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