A HIGHER-ORDER GENUS INVARIANT AND KNOT FLOER HOMOLOGY

PETER D. HORN

Abstract. It is known that knot Floer homology detects the genus and Alexander polynomial of a knot. We investigate whether knot Floer homology detects more structure of minimal genus Seifert surfaces for $K$. We define an invariant of algebraically slice, genus one knots and provide examples to show that knot Floer homology does not detect this invariant. Finally, we remark that certain metabelian $L^2$-signatures bound this invariant from below.

1. Introduction

Knot Floer homology was defined by Peter Ozsváth and Zoltán Szabó [OS04b] and by Jacob Rasmussen [Ras03]. Knot Floer homology is a powerful knot invariant, and it detects such information as the Alexander polynomial [OS04b][Ras03] and knot genus [OS04a, Theorem 1.2]. Either of these invariants can be computed from a minimal genus Seifert surface. We investigate whether knot Floer homology contains more information about any minimal genus Seifert surface.

In [Hor09], the author defined a geometric invariant for knots in $S^3$ called the first-order genus. Roughly, the first-order genus of $K$ is obtained by adding the individual genera (in $S^3 - K$) of the curves in a symplectic basis on a minimal genus Seifert surface for $K$, and taking the minimum over all minimal genus Seifert surfaces. The first-order genus of a knot is difficult to compute, as there are many symplectic bases for a given Seifert surface. While difficult to compute in general, the first-order genus is a notion of higher-order genus defined for all knots.

In this paper, we define a similar invariant, though it is only defined for algebraically slice, genus one knots. We take a minimum over Seifert surfaces, but what we record is the genus (in $S^3 - K$) of a basis curve which inherits the zero framing from the surface. We will provide many examples and show that this invariant is not detected by knot Floer homology.

Theorem 1. Knot Floer homology does not detect the knottedness of untwisted bands in a Seifert surface.

Cochran, Harvey and Leidy [CHL08] defined the first-order $L^2$-signatures of a knot. By their definition, each algebraically slice, genus one knot has (at most) three first-order $L^2$-signatures. We will discuss the relationship between our higher-order genus invariant and these first-order $L^2$-signatures.

2. Motivation and definition

Let $\Sigma_g$ be a compact, oriented surface with one boundary component. If $f: \Sigma_g \hookrightarrow S^3$ is an embedding with $K = f(\partial \Sigma_g)$, then some invariants of $K$ can be computed using this embedded surface $f(\Sigma_g)$. Such an surface is called a Seifert surface for $K$. For example, any Seifert surface can be used to compute the knot’s Alexander polynomial. This polynomial is encoded in the knot Floer homology $\widehat{HF}(K)$. The smallest genus of such embedded surfaces with boundary $K$ is called the genus of $K$, $g(K)$, and this invariant is also detected by $\widehat{HF}(K)$. We naively ask whether $\widehat{HF}(K)$ contains anymore information about the embedded surfaces with boundary $K$. For example, we are interested in whether $\widehat{HF}(K)$ contains information about the knottedness of certain simple closed curves on Seifert surfaces $f(\Sigma_g)$ for $K$. In this paper we will restrict our attention to genus one, algebraically slice knots.

Our motivating example is the positively-clasped, untwisted Whitehead double of a knot $K$, denoted $D(K)$ and depicted in Figure 1. There is an obvious genus one Seifert surface for $D(K)$. In [Hor09], the author defined a knot invariant that measures the knottedness of the bands in Seifert surface for a knot.
For many knots $K$, this invariant applied to $D(K)$ ‘detects’ the genus of $K$, i.e. $g_1(D(K)) = 1 + g(K)$. One may ask if $\widehat{HF}(D(K))$ detects $g_1(D(K)) \approx g(K)$, and by Hedden’s formula [Hed07, Theorem 1.2], the answer is ‘yes’ in the sense that $\widehat{HF}(D(K), 1)$ has as a direct summand $\bigoplus_{j=-g(K)}^{g(K)} G_j(K)$, where the $G_j(K)$ are certain groups depending on $K$. Due to computational difficulties, it is unknown whether $\widehat{HF}(K)$ detects $g_1(K)$ in general. We aim to define an invariant that is more computable than $g_1$ and which measures, more or less, the same thing.

**Definition 1.** Let $K$ be an algebraically slice knot in $S^3$ of genus one. Let $\Sigma$ be any genus one Seifert surface for $K$. Then $\Sigma$ has a metabolizer $m$, a rank one submodule of $H_1(\Sigma; \mathbb{Z})$ on which the Seifert form vanishes. One can show that $\Sigma$ has exactly two metabolizers $m_1$ and $m_2$. Let $[\alpha_1]$ and $[\alpha_2] \in H_1(\Sigma; \mathbb{Z})$ be generators of $m_1$ and $m_2$, respectively. By the classification of essential closed curves on a punctured torus [Min99], each $[\alpha_i]$ determines a unique oriented knot in $\Sigma$; denote this knot by $\alpha_i$. The knot $\alpha_i$ is called a derivative of $K$ with respect to the metabolizer $m_i$.

To sum up, each genus one Seifert surface $\Sigma$ for an algebraically slice knot $K$ has exactly two (up to orientation) derivatives $\alpha_1$ and $\alpha_2$. We denote this set of derivatives as $\partial(K, \Sigma) = \{\alpha_1, \alpha_2\}$.

Let $G(K)$ denote the set of isotopy classes (in $S^3 - K$) of genus one Seifert surfaces for $K$, and if $\alpha$ is a null-homologous knot in $S^3 - K$, let $g^K(\alpha)$ denote the genus of $\alpha$ in $S^3 - K$. We define the differential genus of $K$ to be

$$dg(K) = \min_{\Sigma \in G(K)} \left\{ \max_{\partial(K, \Sigma) = \{\alpha_1, \alpha_2\}} \{g^K(\alpha_1), g^K(\alpha_2)\} \right\}$$

**Remark.** The differential genus measures the knottedness of self-linking zero curves on (genus one) Seifert surfaces for $K$. One may define metabolizers and derivatives of algebraically slice knots of higher genus (see [CHL08]), but in the higher genus setting, a metabolizer may have infinitely many distinct derivatives. One may try to generalize the definition of differential genus to higher genus algebraically slice knots; this may be taken up in a future paper.

### 3. Examples

**Example 1.** Let $K$ be a knot that is non-trivial and not a cable. By [Whi73], the untwisted Whitehead double of $K$, $D(K)$, has a unique minimal genus Seifert surface. Each of the untwisted curves on this Seifert surface have the same knot type as $K$. One can further argue that $dg(D(K)) = g(K)$.

**Example 2.** Let $R = 9_{46}$ as depicted in Figure 2. A symplectic basis of curves $\alpha$ and $\beta$ have been drawn for the implied Seifert surface $\Sigma$. One can check that $\alpha$ and $\beta$ have self-linking zero, and so the two derivatives for $\Sigma$ are $\alpha$ and $\beta$. Each of $\alpha$ and $\beta$ is unknotted, however $g^K(\alpha) = g^K(\beta) = 1$. The knot Floer homology of $R$ is

$$
\begin{array}{ccc}
0 & 0 & 2 \\
0 & 5 & 0 \\
2 & 0 & 0
\end{array}
$$
where the 5 appears in bigrading $(0, 0)$. The genus of $R$ is one, and since rank $\widehat{HF}(R, 1) = 2 < 4$, we may apply Theorem 2.3 of [Juh08] to conclude that $\Sigma$ is the unique genus one Seifert surface for $R$ up to isotopy. We conclude that $dg(R) = 1$.

\begin{figure}[h]
\centering
\includegraphics[width=0.3\textwidth]{figure2.png}
\caption{The 946 knot}
\end{figure}

**Example 3.** Now consider the knot $K_n$ in Figure 3 where $n \in \mathbb{N}$. Observe that $K_0 = 9_{46}$. A symplectic basis of curves $x$ and $y$ have been drawn for the implied Seifert surface $F$. One can check the Seifert form of $F$ to be

$$
\begin{pmatrix}
3n & -2 \\
-1 & 0
\end{pmatrix}
$$

The two curves of self-linking zero are $\alpha_n = x + ny$ and $\beta_n = y$. As in the calculation for $9_{46}$, one can check that $g^{K_n}(\beta_n) = 1$. The other curve $\alpha_n$ is more complicated; see Figure 3. The knot $\alpha_n$ can be represented by the braid on $n + 1$ strands depicted in Figure 3.

\begin{figure}[h]
\centering
\includegraphics[width=0.3\textwidth]{figure3.png}
\caption{A diagram for $K_n$, and a basis for a Seifert surface}
\end{figure}

By [Cro89, Corollary 4.1], the Seifert surface constructed by applying Seifert’s algorithm to the braid diagram in Figure 3 has minimal genus. In particular $g(\alpha_n) = n$, and hence $g^{K_n}(\alpha_n) \geq n$. We must argue that $dg(K_n) \geq n$. For a given $n$, one may easily construct a grid diagram for $K_n$. For several small values of $n$, we used Marc Culler’s Gridlink [Cul] to compute the knot Floer homology of $K_n$. We found that $\widehat{HF}(K_n) \cong \widehat{HF}(9_{46})$ for these values of $n$ (although this family is defined for $n \in \mathbb{N}$, we verified the computation for $n = -1, -\frac{2}{3}, -\frac{1}{3}, 0, \frac{1}{3}, \frac{2}{3}, 1$). A recent result of M. Hedden [Hed08] implies that $\widehat{HF}(K_n) \cong \widehat{HF}(9_{46})$ for all $n$. By [Juh08], $F$ is the unique genus one Seifert surface for $K_n$. By previous arguments, we conclude that $dg(K_n) = g^{K_n}(\alpha_n) \geq g(\alpha_n) \geq n$. 

Figure 4. A knot diagram of $\alpha_n$, a curve of self-linking zero

Figure 5. A braid representative of $\alpha_n$ using $n+1$ strands

Theorem 1 follows.

Remark. One can show by calculating the Alexander polynomials of the unknotted curves for $K_{1/3}$ that $dg\left(K_{1/3}\right) \geq 2$. Thus, $K_{1/3}$ is an explicit example of a knot with the same knot Floer homology as $9_{46}$ and distinct differential genus. The knot $K_{1/3}$ is called 11$_{n_{139}}$ in the knot tables [CL09].

Theorem 2. There exists an infinite family of knots $K_n$ such that

- $\tilde{HFK}(K_n) \cong \tilde{HFK}(K_m)$ for all $m$ and $n$, and
- $\text{dg}(K_n) \neq \text{dg}(K_m)$ for $m \neq n$.

Proof. The family is constructed by taking a subsequence of the knots $K_n$ from Example 3. \qed

4. First-order $L^2$-signatures and the differential genus

Metabelian signatures of knots have been defined by Casson-Gordon, Letsche, Cochran-Orr-Teichner, Friedl, and Cochran-Harvey-Leidy [CG78] [CG86] [Let00] [COT03] [Fri04] [CHL08]. We are interested in those of Cochran, Harvey, and Leidy because each genus one, algebraically slice knot has two “first-order $L^2$-signatures.” We now recall some of the background needed to define these signatures.

Suppose $K$ is an oriented knot in $S^3$, $M_K$ denote the closed, oriented 3-manifold obtained by zero-surgery on $K$, and $G = \pi_1(M_K)$. Let $G^{(1)}$ denote the commutator subgroup of $G$ and $G^{(2)}$ the commutator subgroup of $G^{(1)}$. The classical rational Alexander module of $K$ is

$$\mathcal{A}_0(K) := \frac{G^{(1)}}{G^{(2)}} \otimes_{\mathbb{Z}[t,t^{-1}]} \mathbb{Q} \left[ t, t^{-1} \right]$$
Here $G^{(1)}/G^{(2)}$ is identified with the classical Alexander module $H_1(M_K; \mathbb{Z}[t, t^{-1}])$. The Blanchfield pairing of $K$

$$B_{t0}^K : \mathcal{A}_0(K) \times \mathcal{A}_0(K) \to \mathbb{Q}(t)/\mathbb{Z}[t, t^{-1}]$$

is defined by

$$B_{t0}^K(x, y) = \sum_{n \in \mathbb{Z}} \frac{(d \cdot yt^n) t^n}{\Delta_K(t)}$$

where $\Delta_K(t)$ is the Alexander polynomial of $K$ and $d$ is a 2-chain with $\partial d = \Delta_K(t) \cdot x$. We say a submodule $P \subset \mathcal{A}_0(K)$ is Lagrangian (respectively isotropic) if $P = P^\perp$ (respectively $P \subset P^\perp$) with respect to the Blanchfield pairing. To a submodule $P \subset \mathcal{A}_0(K)$, we can associate a metabelian quotient $\phi_P : G \to G/P$ by setting $\tilde{P} = \ker (G^{(1)} \to G^{(1)}/G^{(2)} \to \mathcal{A}_0(K) \to \mathcal{A}_0(K)/P)$. To this quotient we can associate a real number, called the Cheeger-Gromov von Neumann $\rho$-invariant, $\rho(M_K, \phi_P)$ [CG83] (see Chapter ?? for a description).

**Definition 2.** The first-order $L^2$-signatures of a knot $K$ are the real numbers $\rho(M_K, \phi_P)$ where $P$ is a Lagrangian submodule of $\mathcal{A}_0(K)$ with respect to $B_{t0}^K$.

**Remark.** These are a subset of the metabelian $L^2$-signatures of Cochran, Harvey, and Leidy [CHL08, Definition 4.1], who allow for $P$ to be isotropic.

Assume $K$ is a genus one, algebraically slice knot with a Seifert surface $\Sigma$. The reader will recall that $H_1(\Sigma; \mathbb{Z})$ generates $\mathcal{A}_0(K)$ as a $\mathbb{Q}[t, t^{-1}]$-module (one must pick a lift of $\Sigma$ to the infinite cyclic cover). If $\Delta_K(t) = 1$, then $\mathcal{A}_0(K) = 0$ has no Lagrangian submodules. On the other hand, if $\Delta_K(t) \neq 1$, then $\Delta_K(t) = f(t)f(t^{-1})$ for some linear polynomial $f(t)$. $\mathcal{A}_0(K)$ must be isomorphic to $\mathbb{Q}[t, t^{-1}]$. Thus, any proper submodule $P$ must be

$$\mathbb{Q}[t, t^{-1}] / \langle f(t) \rangle \quad \text{or} \quad \mathbb{Q}[t, t^{-1}] / \langle f(t^{-1}) \rangle$$

Since the Blanchfield pairing is primitive, $\mathcal{A}_0(K)$ will have precisely two Lagrangians. By the Definitions[1], $K$ will have precisely two Lagrangians and hence two first-order $L^2$-signatures.

**Definition 3.** Suppose $P \subset \mathcal{A}_0(K)$ is a Lagrangian. The metabolizer $m$ represents $P$ if the image of $m$ under the map

$$i_\ast \circ (\text{id} \otimes 1) : H_1(\Sigma; \mathbb{Z}) \hookrightarrow H_1(\Sigma; \mathbb{Z}) \otimes \mathbb{Q} \to \mathcal{A}_0(K)$$

spans $P$ as a $\mathbb{Q}$-vector space. (To define $i_\ast$, it is necessary to choose a lift of $\Sigma$ to the infinite cyclic cover, but this definition is independent of the choice).

**Proposition 1** (Lemma 5.5 of [CHL08]). Let $K$ be an algebraically slice knot and $P$ be a Lagrangian of $\mathcal{A}_0(K)$. If $\Sigma$ is any Seifert surface for $K$, then some metabolizer of $H_1(\Sigma)$ represents $P$.

**Proposition 2** (Corollary 5.8 of [CHL08]). Let $K$ be a genus one, algebraically slice knot. Suppose $P$ is a Lagrangian for $K$, $\Sigma$ is a genus one Seifert surface for $K$, $m$ is the metabolizer of $\Sigma$ representing $P$, and $J$ is the derivative with respect to $m$. Then the first-order $L^2$-signature of $K$ with respect to $P$ is equal to $\rho_0(J) = \int_{\sigma_1} \sigma \omega(J) d\omega$, the integral of the Levine-Tristram signature function.

Determining $dg(K)$ involves computing the genus of two curves from each genus one Seifert surface, of which there may be many. Examples of knots that have an arbitrary number of non-isotopic Seifert surfaces are known [Suz91, p. 47]. Yet we have the following remarkable fact: if just one of the first-order $L^2$-signatures is large, then the differential genus must be large.

**Proposition 3.** Let $K$ be a genus one, algebraically slice knot with non-trivial Alexander polynomial. Let $\rho_1$ and $\rho_2$ denote the first-order $L^2$-signatures of $K$ with respect two the two Lagrangians $P_1$ and $P_2$. Then $2dg(K) \geq \max\{|\rho_1|, |\rho_2|\}$. 
Proof. Let $\Sigma$ be the Seifert surface where the minimum is attained. For either derivative $J_i \subset \Sigma$, where $J_i$ represents the Lagrangian $P_i$, we have

$$2 \, dg(K) \geq 2 \, g^K(J_i) \geq \left| \int_{S^1} \sigma_\omega(J_i) \, d\omega \right| \geq |\rho_i|$$

\[ \square \]

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Department of Mathematics, Rice University, 6100 S. Main Street, Houston, TX 77005

E-mail address: phorn@rice.edu

URL: http://math.rice.edu/~phorn