An open book decomposition compatible with rational contact surgery

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Dedicated to the memory of Raoul Bott.

ABSTRACT. We construct an open book decomposition compatible with a contact structure given by a rational contact surgery on a Legendrian link in the standard contact S^3. As an application we show that some rational contact surgeries on certain Legendrian knots induce overtwisted contact structures.

0. Introduction

Recently Giroux proved a central result regarding the topology of contact 3-manifolds. Namely he established a one to one correspondence between contact structures up to isotopy and open book decompositions up to positive stabilizations. This correspondence, however, does not explicitly describe an open book decomposition corresponding to a given contact structure.

In [DG], Ding and Geiges proved that every (closed) contact 3-manifold (Y, ξ) can be given by a contact (± 1)-surgery on a Legendrian link in the standard contact S^3. Here we use the parenthesis to emphasize that the surgery coefficients are measured with respect to the contact framing. If the coefficients of all the curves in a contact surgery diagram are (-1), then an open book decomposition compatible with this contact structure is given by the algorithm in [AO] coupled with the work of Plamenevskaya ([P]). Moreover, Stipsicz ([S]) showed that the same algorithm works in the general case of contact (± 1)-surgery. In this article we will review these results (giving slightly different proofs) and extend the algorithm to the case of rational contact surgery.

In fact any rational contact surgery can be turned into a sequence of contact (± 1)-surgeries ([DG, DGS]) and the algorithm above would provide an open book decomposition compatible with the resulting contact structure. However, this would give an open book decomposition with high genus and we will show that there is a short-cut in obtaining an open book decomposition (with lower genus) compatible with a rational contact surgery.

As an application we show that certain rational contact surgeries induce overtwisted contact structures by making use of the right-veering property of tight contact structures recently introduced by Honda, Kazez and Matic ([HKM]).

Here we outline the main idea in this article. Given a Legendrian link in the standard contact (S^3, ξ_{st}) with its front projection onto the yz-plane. We will show that there is an open book decomposition on S^3 compatible with a contact structure ξ_0 isotopic to ξ_{st} such that the Legendrian link (after a Legendrian isotopy) is contained in a page of this open book decomposition as described in [P]. It follows that the page framing and the contact framing coincide on each component of this link since the Reeb vector field induces both framings. Consequently when we perform contact (± 1)-surgery on this link we get an open book decomposition compatible with the resulting contact structure. The monodromy of this open book decomposition is given by a product of Dehn twists along curves explicitly drawn on a page. Now when a Legendrian link with rational surgery coefficients is given, we embed this link into the page of the open book decomposition as described above. Then we attach appropriate 1-handles to a page of this open book decomposition and extend the monodromy of our open book decomposition by Dehn twists along some push-offs of the original monodromy curves going through the attached 1-handles.

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1. Open book decompositions and contact structures

We will assume that all our contact structures are positive and cooriented. In the following we describe the compatibility of an open book decomposition with a given contact structure on a 3-manifold.

Definition 1. *Suppose that for a link L in a 3-manifold Y the complement $Y - L$ fibers as $\pi \colon Y - L \to S^1$ such that the fibers are interiors of Seifert surfaces of L. Then (L, π) is an* open book decomposition *of Y. The Seifert surface $F = \overline{\pi^{-1}(t)}$ is called a* page, *while L the* binding *of the open book decomposition. The monodromy of the fibration π is called the* monodromy *of the open book decomposition.*

Any locally trivial bundle with fiber F over an oriented circle is canonically isomorphic to the fibration $I \times F/(1, x) \sim \big(0, h(x)\big) \to I/\partial I \approx S^1$ for some self-diffeomorphism h of F. In fact, the map h is determined by the fibration up to isotopy and conjugation by an orientation preserving self-diffeomorphism of F. The isotopy class represented by the map h is called the monodromy of the fibration. Conversely given a compact oriented surface F with nonempty boundary and $h \in \Gamma_F$ (the mapping class group of F) we can form the mapping torus $F(h) = I \times F/(1, x) \sim \big(0, h(x)\big)$. Since h is the identity on ∂F, the boundary $\partial F(h)$ of the mapping torus $F(h)$ can be canonically identified with r copies of $T^2 = S^1 \times S^1$, where the first S^1 factor is identified with $I/\partial I$ and the second one comes from a component of ∂F. Hence by gluing in r copies of $D^2 \times S^1$ to $F(h)$ so that ∂D^2 is identified with $S^1 = I/\partial I$ and the S^1 factor in $D^2 \times S^1$ is identified with a boundary component of ∂F, $F(h)$ can be completed to a closed 3-manifold Y equipped with an

open book decomposition. In conclusion, an element $h \in \Gamma_F$ determines a 3-manifold together with an "abstract" open book decomposition on it.

Theorem 2 (Alexander). *Every closed and oriented 3-manifold admits an open book decomposition.*

Suppose that an open book decomposition with page F is specified by $h \in \Gamma_F$. Attach a 1-handle to the surface F connecting two points on ∂F to obtain a new surface F'. Let α be a closed curve in F' going over the new 1-handle exactly once. Define a new open book decomposition with $h \circ t_\alpha \in \Gamma_{F'}$, where t_α denotes the right-handed Dehn twist along α. The resulting open book decomposition is called a *positive stabilization* of the one defined by h. If we use a left-handed Dehn twist instead then we call the result a *negative stabilization*. The inverse of the above process is called *positive (negative) destabilization*. Note that the topology of the underlying 3-manifold does not change when we stabilize/destabilize an open book. Also note that the resulting monodromy depends on the chosen curve α.

Definition 3. *An open book decomposition of a 3-manifold Y and a contact structure ξ on Y are called* compatible *if ξ can be represented by a contact form α such that the binding is a transverse link, $d\alpha$ is a volume form on every page and the orientation of the transverse binding induced by α agrees with the boundary orientation of the pages.*

In other words, the conditions that $\alpha > 0$ on the binding and $d\alpha > 0$ on the pages is a strengthening of the contact condition $\alpha \wedge d\alpha > 0$ in the presence of an open book decomposition on Y. The condition that $d\alpha$ is a volume form on every page is equivalent to the condition that the Reeb vector field of α is transverse to the pages. Moreover an open book decomposition and a contact structure are compatible if and only if the Reeb vector field of α is transverse to the pages (in their interiors) and tangent to the binding.

Theorem 4 (Giroux). *Every contact 3-manifold admits a compatible open book decomposition.*

2. An open book decomposition compatible with a contact (± 1)-surgery

In this section we describe an explicit construction of an open book decomposition compatible with a given contact structure. The algorithm is contained in [AO] and it is proven to be compatible with the given contact structure in [P] and [S].

We will show that for a given Legendrian link $\mathbb{L}$ in $(\mathbb{R}^3, \xi_{st}) \subset (S^3, \xi_{st})$ there exists a surface $F \subset S^3$ containing $\mathbb{L}$ such that $d\alpha$ is an area form on F (where $\alpha = dz + x\, dy$), $\partial F = K$ is a torus knot which is transverse to $\xi_{st} = \ker \alpha$ and the components of $\mathbb{L}$ do not separate F. We first isotope $\mathbb{L}$ by a Legendrian isotopy so that in the front projection (onto the yz-plane) all the segments have slope (± 1) away from the points where $\mathbb{L}$ intersects the yz-plane. Then we consider narrow rectangular strips around each of these segments and connect them by small twisted bands corresponding to each point where $\mathbb{L}$ intersects the yz-plane. The small bands can be constructed in such a way that

the Legendrian link lies on these bands while the bands twist along the contact planes. The narrow strips around the straight segments connected with these small twisted bands give us the Seifert surface F of a torus knot $K = \partial F$. Notice that we ensured that $\mathbb{L}$ lies in F. Moreover $d\alpha$ is an area form on F by construction since the Reeb vector field $\frac{\partial}{\partial z}$ of α is transverse to F. Furthermore we can slightly isotope $\partial F = K$ to make it transverse to ξ_{st}.

Now since K is a fibered knot with fibered surface F there is a fibration of the complement of K in S^3 where F is one of the pages of the induced open book decomposition on S^3. Note that $d\alpha$ induces an area form on the nearby pages as well since we can always keep the nearby pages transverse to $\frac{\partial}{\partial z}$. The union of these nearby pages including the binding K is a handlebody U_1 (which is a thickening of this one page F that carries the Legendrian link $\mathbb{L}$) such that $d\alpha$ is an area form on every page. But we can not guarantee that $d\alpha$ induces an area form on the rest of the pages of this open book decomposition. We would like to extend the contact structure ξ_{st} to the complementary handlebody U_2 (as some contact structure ξ_0) so that it is compatible with the pages in U_2. This can be achieved (see [P]) by an explicit construction of a contact form on U_2 similar to the one described in [TW]. Hence we get a contact structure ξ_0 on S^3 which is compatible with our open book. Moreover, by construction ξ_0 and ξ_{st} coincide on U_1 and we claim that the contact structures ξ_0 and ξ_{st} are isotopic on U_2 relative to ∂U_2. Notice that ∂U_2 can be made convex and one can check that the binding K is the dividing set on ∂U_2. Uniqueness (up to isotopy) of a tight contact structure with such boundary conditions is given by Theorem 5.

Suppose that (K, π) is a given open book decomposition on a closed 3-manifold Y. Then by presenting the circle S^1 as the union of two closed (connected) arcs $S^1 = I_1 \cup I_2$ intersecting each other in two points, the open book decomposition (K, π) naturally induces a *Heegaard decomposition* $Y = U_1 \cup_\Sigma U_2$ of the 3-manifold Y. The surface Σ along which these handlebodies are glued is simply the union of two pages $\pi^{-1}(I_1 \cap I_2)$ together with the binding.

Theorem 5 (Torisu, [To])**.** *Suppose that ξ_1, ξ_2 are contact structures on Y satisfying:*
(i) $\xi_i|_{U_j}$ $(i = 1, 2; \ j = 1, 2)$ *are tight, and*
(ii) Σ *is convex in (Y, ξ_i) and K is the dividing set for both contact structures.*
Then ξ_1 and ξ_2 are isotopic. In addition, the set of such contact structures is nonempty.

Summarizing the above discussion we get

Proposition 6 (Plamenevskaya, [P])**.** *For a given Legendrian link $\mathbb{L}$ in (S^3, ξ_{st}) there exists an open book decomposition of S^3 satisfying:*
(1) *the contact structure ξ_0 compatible with this open book decomposition is isotopic to ξ_{st},*
(2) $\mathbb{L}$ *is contained in one of the pages and none of the components of $\mathbb{L}$ separate F,*
(3) $\mathbb{L}$ *is Legendrian with respect to ξ_0,*
(4) *there is an isotopy which fixes $\mathbb{L}$ and takes ξ_0 to ξ_{st},*

(5) *the page framing of $\mathbb{L}$ (induced by F) is the same as its contact framing induced by ξ_0 (or ξ_{st}).*

In fact item (5) in the theorem above follows from (1)-(4) by

Lemma 7. *Let C be a Legendrian curve on a page of a compatible open book decomposition $\mathfrak{ob}_\xi$ in a contact 3-manifold (Y, ξ). Then the page framing of C is the same as its contact framing.*

Proof. Let α be the contact 1-form for ξ such that $\alpha > 0$ on the binding and $d\alpha > 0$ on the pages of $\mathfrak{ob}_\xi$. Then the Reeb vector field R_α is transverse to the pages (in their interiors) as well as to the contact planes. Hence R_α defines both the page framing and the contact framing on C. $\qquad\square$

Given a Legendrian link $\mathbb{L}$ in $(\mathbb{R}^3, \xi_{st}) \subset (S^3, \xi_{st})$ we described an open book decomposition on S^3 whose page is the Seifert surface of an appropriate torus knot K and $\mathbb{L}$ is included in one of the pages. When we perform contact (± 1)-surgery along $\mathbb{L}$ we get a new open book decomposition on the resulting contact 3-manifold obtained by the surgery. The monodromy of this open book decomposition is given by the composition of the monodromy of the torus knot and Dehn twists along the components of the surgery link. Here all the Dehn twists of the monodromy of the torus knot is right-handed while a $(+1)$-surgery curve (resp. (-1)) induces a left-handed (resp. right-handed) Dehn twist. Notice that the surgery curves are pairwise disjoint and they are homologically non-trivial on the Seifert surface by this construction. It turns out that the resulting contact 3-manifold and the open book decomposition are compatible by the following theorem a proof of which is can be found in [G] in case of (-1)-surgery and [E1] for the general case.

Proposition 8. *Let C be a Legendrian curve on a page of a compatible open book decomposition $\mathfrak{ob}_\xi$ with monodromy $h \in \Gamma_F$ on a contact 3-manifold (Y, ξ). Then the contact 3-manifold obtained by contact (± 1)-surgery along C is compatible with the open book decomposition with monodromy $h \circ (t_C)^{\mp 1} \in \Gamma_F$, where t_C denotes a right-handed Dehn twist along C.*

3. An open book decomposition compatible with a rational contact surgery

In this section we will first outline how to turn a rational contact surgery into a sequence of contact (± 1)-surgeries. The reader is advised to consult [DG, DGS] for background on contact surgery.

Assume that we want to perform contact (r)-surgery on a Legendrian knot L in (S^3, ξ_{st}) for some rational number $r < 0$. In this case the surgery can be replaced by a sequence of contact (-1)-surgeries along Legendrian knots associated to L as follows: suppose that $r = -\frac{p}{q}$ and the continued fraction coefficients of $-\frac{p}{q}$ are equal to $[r_0 + 1, r_1, \ldots, r_k]$, with $r_i \leq -2$ $(i = 0, \ldots, k)$. Consider a Legendrian push-off of L, add $|r_0 + 2|$ zig-zags to it and get L_0. Push this knot off along the contact framing and add $|r_1 + 2|$ zig-zags to it

to get L_1. Perform contact (-1)-surgery on L_0 and repeat the process with L_1. After $(k+1)$ steps we end up with a diagram involving only contact (-1)-surgeries. The result of the sequence of contact (-1)-surgeries is the same as the result of the original contact (r)-surgery according to [DG, DGS].

Proposition 9 (Ding–Geiges, [DG])**.** *Fix $r = \frac{p}{q} > 0$ and an integer $k > 0$. Then contact (r)-surgery on the Legendrian knot L is the same as contact $(\frac{1}{k})$-surgery on L followed by contact $(\frac{p}{q-kp})$-surgery on the Legendrian push-off L' of L.*

By choosing $k > 0$ large enough, the above proposition provides a way to reduce a contact (r)-surgery (with $r > 0$) to a contact $(\frac{1}{k})$-surgery and a negative contact (r')-surgery. This latter one can be turned into a sequence of contact (-1)-surgeries, hence the algorithm is complete once we know how to turn contact $(\frac{1}{k})$-surgery into contact (± 1)-surgeries.

Lemma 10 (Ding–Geiges, [DG])**.** *Let $L_1, \cdots, L_k$ denote k Legendrian push-offs of the Legendrian knot L. Then contact $(\frac{1}{k})$-surgery on L is isotopic to performing contact $(+1)$-surgeries on the k Legendrian knots $L_1, \cdots, L_k$.*

Given a Legendrian link $\mathbb{L}$ in $(\mathbb{R}^3, \xi_{st}) \subset (S^3, \xi_{st})$ with rational surgery coefficients. We follow the algorithm described in Section 2 to find an open book decomposition on S^3 such that $\mathbb{L}$ is embedded in one of the pages. Now use the above algorithm to turn the rational surgery into contact (± 1)-surgeries. Since the contact framing of each component of $\mathbb{L}$ agrees with the page framing by Lemma 7, a contact push-off of any component will still lie on the same page.

Let L be a Legendrian knot in $(\mathbb{R}^3, \xi_{st})$. We define the positive and negative stabilization of L as follows: First we orient the knot L and then if we replace a strand of the knot by an up (down, resp.) cusp by adding a zigzag as in Figure 1 we call the resulting Legendrian knot the negative (positive, resp.) stabilization of L. Notice that stabilization is a well defined operation, i.e., it does not depend at which point the stabilization is done.
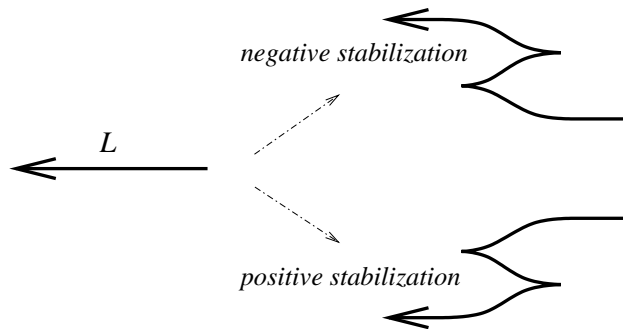

FIGURE 1. Positive and negative stabilization of a Legendrian knot L

Now let L be a Legendrian knot in a page of a compatible open book decomposition $\mathfrak{ob}_\xi$ in a contact 3-manifold (Y, ξ). Then by Lemma 3.3 in [E2], the stabilized knot lies in a page of an open book decomposition obtained by stabilizing $\mathfrak{ob}_\xi$ by attaching a 1-handle to the page of $\mathfrak{ob}_\xi$ and letting the stabilized knot go through the 1-handle once. Notice that there is a positive and a negative stabilization of the oriented Legendrian knot L defined by adding a down or an up cusp, and this choice corresponds to adding a *left* (i.e., to the left-hand side of the oriented curve L) or a *right* (i.e., to the right-hand side of the oriented curve L) 1-handle to the surface respectively as shown in Figure 2.
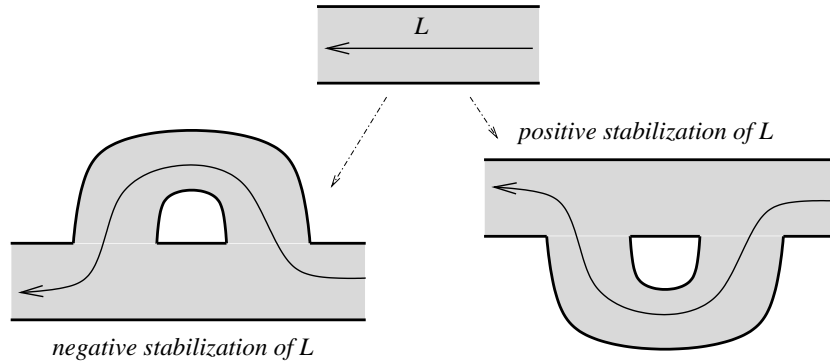
FIGURE 2. Stabilization of a page to include the stabilization of the Legendrian knot L

Repeating this process (by attaching appropriate right or left 1-handles to the Seifert surface of the torus knot) we will get a page of an open book decomposition where we have all the push-offs with their additional zig-zags embedded in this page. Notice that contact (r)-surgery is not uniquely defined because of the choice of adding up or down zig-zags to the push-offs and this choice can be followed in the way that we attach our 1-handles as in Figure 2. The monodromy of the resulting open book decomposition will be the composition of the monodromy of the torus knot (a product of right-handed Dehn twists), right-handed Dehn twists corresponding to the stabilizations and the Dehn twists along the push-offs. This open book decomposition is compatible with the contact (r)-surgery by Proposition 8 since we can recover the effect of this rational surgery on (S^3, ξ_{st}) by contact (± 1)-surgeries along embedded curves on a page of an open book decomposition of S^3 compatible with its standard contact structure. Here notice that when we positively stabilize a compatible open book decomposition of (S^3, ξ_{st}), the resulting open book decomposition (of S^3) will be compatible with ξ_{st}. As a result we get

Theorem 11. *Given a contact 3-manifold obtained by a rational contact surgery on a Legendrian link in the standard contact S^3. Then there is an algorithm to find an open book decomposition on this 3-manifold compatible with the contact structure.*

4. An example

We illustrate the algorithm on a simple example. Consider a contact $(-\frac{5}{3})$-surgery on the right-handed Legendrian trefoil knot L in Figure 3.
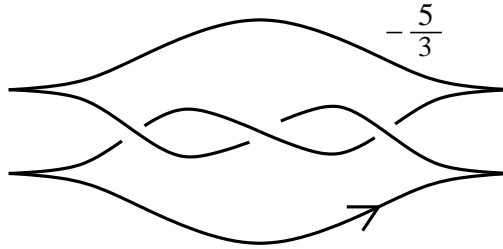

FIGURE 3. Rational contact surgery on a right-handed Legendrian trefoil knot in (S^3, ξ_{st})

Observe first that the continued fraction coefficients of $-\frac{5}{3}$ are $r_0 = r_1 = -3$. Notice that this surgery is not uniquely defined and there are four different possibilities of performing this surgery. We will find an open book decomposition compatible with one of these surgeries. First orient the Legendrian knot as indicated in Figure 3. Consider a Legendrian push-off of L, add a down zig-zag to it and get L_0. Push L_0 off along the contact framing and add a down zig-zag to it to get L_1. Performing contact (-1)-surgery on both L_0 and L_1 is equivalent to performing a contact $(-\frac{5}{3})$-surgery on the right-handed Legendrian trefoil knot in Figure 3. The push-offs L_0 and L_1 are illustrated in Figure 4.

Finally in Figure 5, we depict the page of the open book decomposition which is compatible with the contact $(-\frac{5}{3})$-surgery on the right-handed Legendrian trefoil knot L. The page is the Seifert surface of the (5,6)-torus knot with two 1-handles attached. Notice that the 1-handle attachments in Figure 2 are shown abstractly but in Figure 5 this corresponds to plumbing positive Hopf-bands to the Seifert surface which is embedded in $\mathbb{R}^3$. The push-offs L_0 and L_1 are embedded on this page and the monodromy of the open book decomposition is the product of the monodromy of the (5,6)-torus knot (see [O] for details), right-handed Dehn twists along the embedded curves L_0 and L_1 and right-handed Dehn twists along the core circles of the 1-handles.

5. An application

In [O], we proved that for any positive integer k contact $(\frac{1}{k})$-surgery on a stabilized Legendrian knot in the standard contact S^3 induces an overtwisted contact structure, using sobering arcs introduced by Goodman [Go]. Note that contact $(\frac{1}{k})$-surgery is uniquely defined for any integer $k \neq 0$. In this section we will prove that for any positive rational number r, at least one of the contact (r)-surgeries on a stabilized Legendrian knot induces an overtwisted contact structure, using the *right-veering* arcs introduced by Honda,
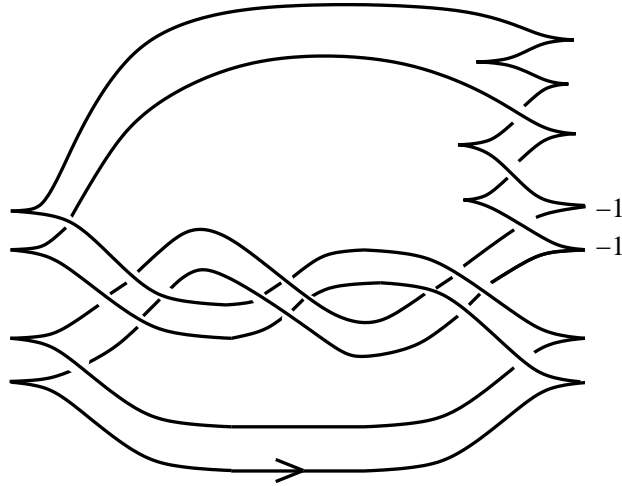
FIGURE 4. Turning rational contact surgery into contact (± 1)-surgeries

Kazez and Matic. Let α and β be two properly embedded oriented arcs in a surface F with boundary. Let $\alpha(0) = \beta(0) = p \in \partial F$. Choose a hyperbolic metric on F and realize α and β as geodesics. If either $(\beta'(0), \alpha'(0))$ forms an oriented basis for T_pF or $\alpha'(0)$ is parallel to $\beta'(0)$ then we call β is to the right of α, denoted by $\beta \geq \alpha$.

Definition 12. *An element $h \in \Gamma_F$ (the mapping class group of F) is right-veering if for every $p \in \partial F$ and for every properly embedded arc α with $\alpha(0) = p$ we have $h(\alpha) \geq \alpha$. An open book decomposition is called right-veering if the monodromy of the open book decomposition is right-veering.*

Theorem 13 (Honda–Kazez–Matic, [HKM])**.** *If a contact 3-manifold (Y, ξ) is tight then every open book decomposition of Y compatible with ξ is right-veering.*

Suppose that K is a positively stabilized Legendrian knot in (S^3, ξ_{st}). Let r be a positive rational number and apply the algorithm in Section 3 to turn a contact (r)-surgery on K into a sequence of contact (± 1)-surgeries along some push-offs of K in such a way that all the push-offs are only negatively stabilized. Now consider the open book we described in Section 3 compatible with this surgery diagram. Since K is already positively stabilized, the page of the compatible open book is obtained by attaching a left 1-handle H_0 and some right 1-handles $H_1, H_2, \cdots, H_n$ (corresponding to the push-offs of K) to the Seifert surface of an appropriate torus knot. Note that all the surgery curves are embedded disjointly on the resulting page of the open book. We claim that the arc α across H_0 (depicted in Figure 6) is not right-veering at its top-end and hence showing that the induced contact structure is overtwisted by the criterion given in Theorem 13.
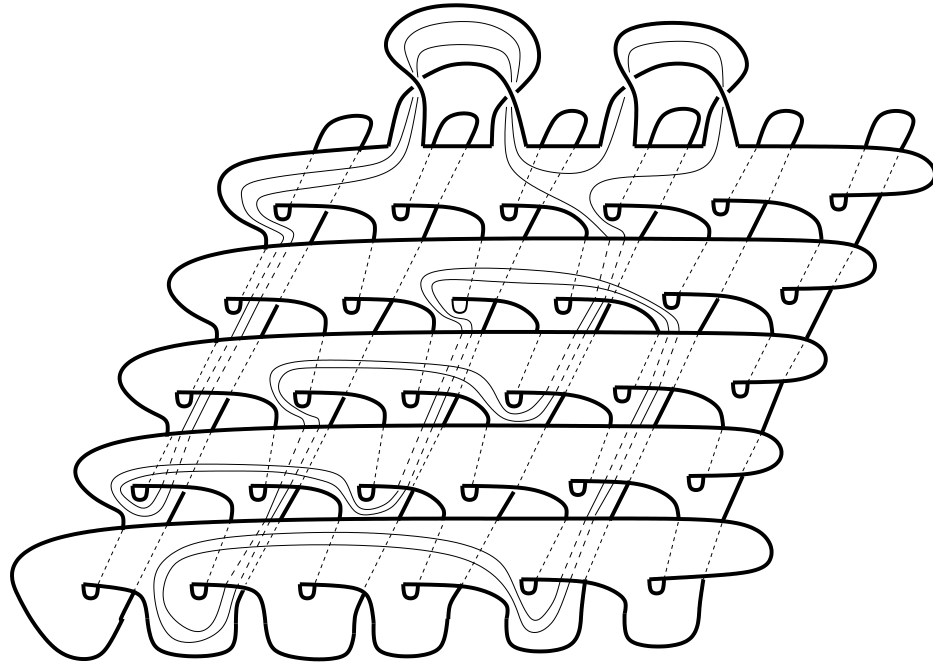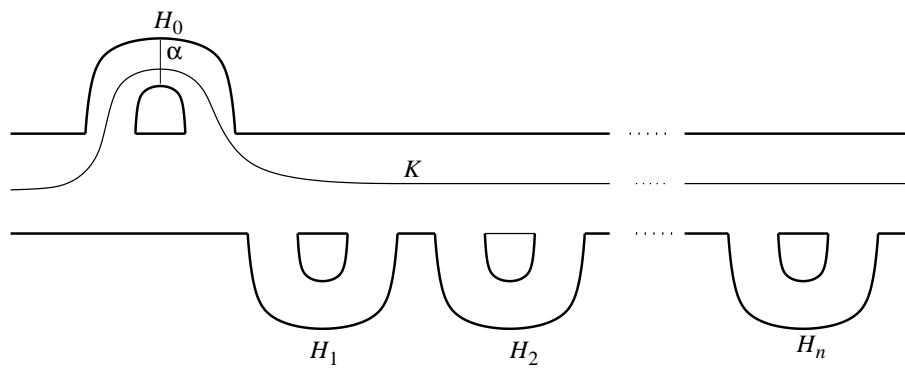
FIGURE 5.

FIGURE 6. Legendrian knot K on the page and the arc α across H_0

To verify that α is not right-veering at its top-end we apply the monodromy h of the open book to α and observe that $h(\alpha)$ lies to the left of α on the page. Here note that the relevant part of the monodromy h consists of a product of k (described by Proposition 9)

left-handed Dehn twists along K, right-handed Dehn twists along the push-offs of K (going through the 1-handles in Figure 6 in various ways) and a right-handed Dehn twist along the core circle of the handle H_0. The key point is that all the curves along which we apply right-handed Dehn twists stay only on one side of K on the surface and a cancellation of a left-handed Dehn twist by a right-handed Dehn twist is not allowed by construction. Here we would like to point out that α is not a sobering arc, so we could not use Goodman's criterion (cf. [Go]) to prove overtwistedness of the induced contact structure as we did in [O]. Thus we proved

Proposition 14. *For any positive rational number r, at least one of the contact (r)-surgeries on a stabilized Legendrian knot in the standard contact 3-sphere induces an overtwisted contact structure.*

We depict in Figure 7 an example of a contact structure which is overtwisted by Proposition 14. The contact structure in Figure 7 is obtained by a $\left(\frac{5}{2}\right)$-contact surgery on the Legendrian unknot which is shown in Figure 8. The next result easily follows from Proposition 14:
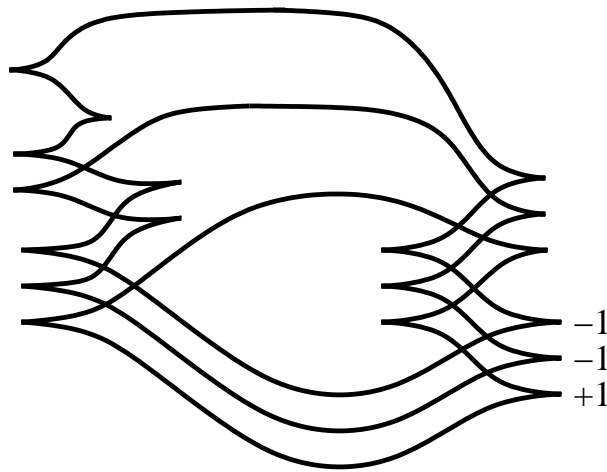

-1
-1
$+1$

FIGURE 7. An overtwisted contact structure

Corollary 15. *If a rational contact surgery diagram contains a Legendrian knot with an isolated stabilized arc whose surgery coefficient is positive then at least one of the surgeries it represents is overtwisted.*
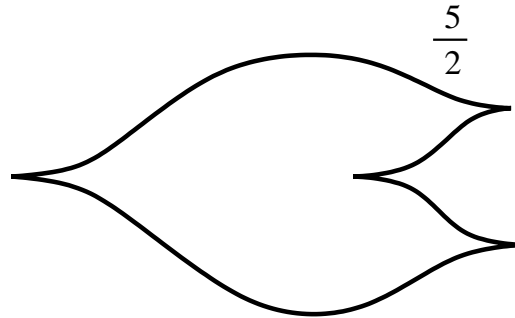
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$$\frac{5}{2}$$

FIGURE 8. $\left(\frac{5}{2}\right)$-contact surgery on a Legendrian unknot

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