Exotic Tori from ATFs oder so

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1 Introduction

Definition 1.1. Let $k \in \mathbb{N}$ such that $0 < k \leq d$ and $a \in (0, \infty)$. Through nodal slides we can arrange the ATF on B_{dpq} such that the line $x_2 = a$ intersects the branch cut line between the $(k-1)$-th and k-th degenerated fibre. $T_k(a)$ is defined to be the fibre over the intersection point of these two lines.

Theorem 1.2. *Let $U \subset H^1(T_k(a), \mathbb{R}) \setminus \{$branch cut line$\}$. The restriction of the displacement energy germ to U is given by*

$$S^e_{T_k(a)}\Big|_U (x, y) = a + \max\{x, x(1 - kpq) - kp^2 y\}$$

so oder so ähnlich...

Let $d, p, q \in \mathbb{N}$ such that $d \geq$ and p, q coprime with $1 \leq q < p$ or $q = 0, p = 1$, and $0 < a_1 < \ldots < a_d$ real integers. Let P be the polynomial $P(z) = \prod_{i=1}^{d} (z^p - a_i)$. Define the manifold M_P by

$$M_P = \left\{ (z_1, z_2, z_3) \in \mathbb{C}^3 \mid z_1 z_2 + P(z_3) = 0 \right\}.$$

We define the Hamiltonian system

$$\mathbf{H}(z_1, z_2, z_3) = \left(|z_3|^2, \frac{1}{2}\left(|z_1|^2 - |z_2|^2 \right) \right)$$

Let μ_p be the group of p-Th roots of unity acting on M_P by

$$\mu \cdot (z_1, z_2, z_3) = \left(\mu z_1, \mu^{-1} z_2, \mu^q z_3 \right), \quad \mu \in \mu_p.$$

This is a free action, so we can define the quotient $B_{dpq} = M_P / \mu_p$. The Hamiltonian system $\mathbf{H}$ is invariant under the action, so it descends to a Hamiltonian system on B_{dpq}.

pass to action-angle coordinates etc.

The position of the nodes can be varied along this ray by nodal slides.

...which only affect some ε-neighboorhood.

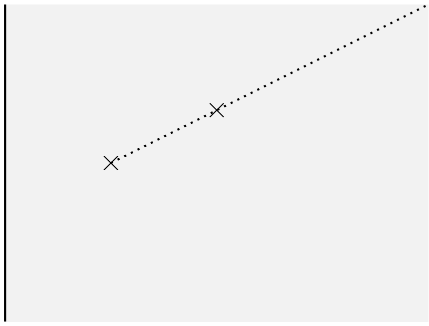
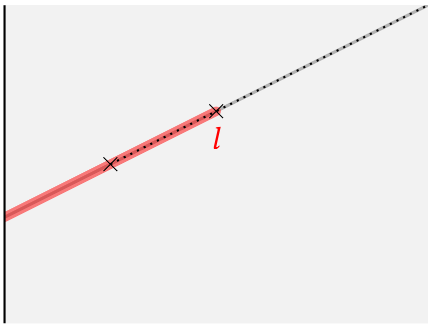
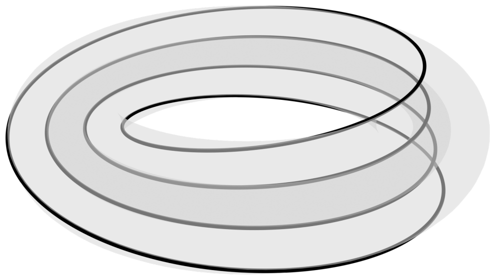


Figure 1: Moment image of B_{dpq} under μ



(a) Retraction to branch cut line



(b) The cycles marked in black (here p=2,q=1) are collapsed to a point.

Figure 2: Calculation of the homology of B_{dpq}

2 Upper bound on displacement energy: Probes

3 Short interlude: Homology of B_{dpq}

In order to calculate the lower bound for the displacement energy of a torus $L(x,y)$, we will need to calculate a basis for $H_2\big(B_{dpq}, L(x,y)\big)$.

definieren

B_{dpq} deformation retracts to the preimage of the branch cut line segment l shown in red in figure 2a, by first vertically shrinking the space onto the ray in direction (p,q), and then compressing the part of the ray that is to the right of all the critical points.

Das ist etwas dumm formuliert, lohnt es sich das besser zu formulieren?

The preimage $\mu^{-1}(l)$ can be understood as follows: If there were no critical points on the line, this would be a solid torus $T = S^1 \times D^2$. We pick $(1,0),(0,1) \in H_1(\partial T)$ to be the classes generated by $S^1 \times \mathrm{pt}, \mathrm{pt} \times \partial D^2$ respectively. For each critical fibre $k \in \{1,\dots,d\}$ we collapse a loop along the homology class $(-q,p)$, as in figure 2b. Up to homotopy this is the same as attaching a disk D_k along $(-q,p)$. Again up to homotopy we can also require that the d discs $D_1,\dots,D_d$ are attached along ∂T. Let us call this space S.

Let us look at the long exact sequence of homology for the pair $\big(B_{dpq}, L(x,y)\big)$.

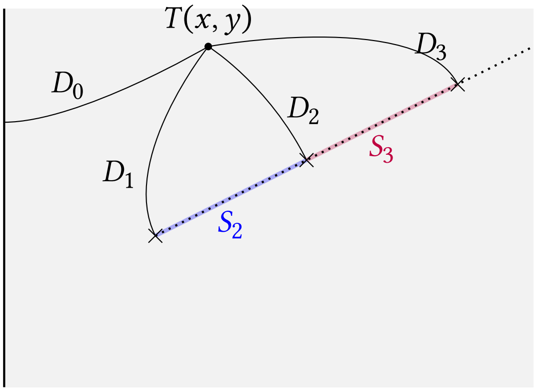


Figure 3: The disks $D_0, \ldots, D_d$ generating the homology $H_2\big(B_{dpq}, L(x,y)\big)$

This pair is homotopy equivalent to $(S, \partial T)$.

$$
\begin{tikzcd}
H_2(\partial T) \arrow[r, "0"] & H_2(S) \arrow[r, hook] \arrow[d, "\cong"] & H_2(S,\partial T) \arrow[r] \arrow[d, "\cong"] & H_1(\partial T) \arrow[r] \arrow[d, "\cong"] & H_1(S) \arrow[d, "\cong"] \\
& \mathbb{Z}^{d-1} & \mathbb{Z}^{d+1} & \mathbb{Z}^2 & \mathbb{Z}_p
\end{tikzcd}
$$

The first horizontal map is zero since ∂T retracts to a circle in S. The homology $H_2(S)$ can be seen as follows: By contracting the solid torus T in S to a circle, we see that S is homotopic to a circle with d discs glued to its boundary by a degree p map. So $H_2(S)$ is generated by spheres $\{S_2, \ldots, S_d\}$, $S_k = D_{k-1} - D_k$. $H_2(S, \partial T)$ is generated by the discs $D_0 = \mathrm{pt} \times D^2, D_1, \ldots, D_d$. In B_{dpq}, these discs can be seen, where the disc intersecting the toric boundary collapses the $(0,1)$ cycle in the toric fibre $L(x,y)$ and the discs intersecting the critical points collapse the $(-q,p)$ cycle (see figure 3). The elements $S_2, \ldots, S_d \in H_2(B_{dpq})$ can be realized by embedded Lagragian spheres fibering over the segments between the nodes in the ATF – these are so-called *visible Lagrangians*, see [3, section 7.4]. The boundary map $\partial\colon H_2(S, \partial T) \to H_1(\partial T)$ is given by $\partial D_0 = (0,1)$, $\partial D_i = (-q,p)$, meaning that the last horizontal map $H_1(\partial T) \to H_1(S)$ maps $(0,1)$ to the generator of $\mathbb{Z}_p$.

4 Lower Bound on Displacement Energy: Minimal J-holomorphic Curves

Let $L(x,y)$ a fibre torus, where (x,y) is not over the branch cut line. In [1] the following is proven:

Theorem 4.1. *Let $L \subset X$ be a Lagrangian submanifold. Then the displacement energy satisfies*

$$e(L) \geq \min\{\sigma_D(X, L, J), \sigma_S(X, J)\}$$

Compact Lagrangian in a tame symplectic manifold. Let J be...

4.1 Displacement energy and exotic tori in B_{dpq}

In this subsection we denote by $L(x_0, y_0)$ the almost toric fibre over the point (x_0, y_0) with $x_0 > 0$. Fibres $L(\lambda p, \lambda q)$ for $\lambda > 0$ are monotone whenever they are not on a node. We compute displacement energy of the non-monotone fibres.Note that $L(x_0, y_0)$ yields a well-defined torus up to Hamiltonian isotopy, i.e. it is independent of the nodal slides, see .

das müsste man auch noch zeigen...

referenz

Proposition 4.2. *Let $L(x_0, y_0)$ be a non-monotone ATF-fibre of B_{dpq}. Then it has displacement energy*

$$e(B_{dpq}, L(x_0, y_0)) = x_0.$$

Proof. The upper bound follows from probes. For the lower bound, we use theorem 4.1 together with lemma 4.3. □

4.1.1 Almost complex structure on B_{dpq}

Let (n, a) be two coprime integers, μ_n the group of n-th roots of unity. Let μ_n act on $\mathbb{C}^2$ by $\mu(z_1, z_2) = (\mu z_1, \mu^a z_2)$. Let $A(n, a) = \mathbb{C}^2/\mu_n$ be the quotient space. This space is an orbifold, with one orbifold point at $[(0, 0)]$. The space S^3/μ_n is the lens space $L(n, a)$, so $A(n, a)$ is the cone over $L(n, a)$.

notation clash!!!

We define the Hamiltonian system on $A(n, a)$ by

$$\mathrm{G}(z_1, z_2) = \frac{1}{2}\left(|z_2|^2, \frac{1}{n}\left(|z_1|^2 + a|z_2|^2\right)\right). \tag{1}$$

With this Hamiltonian system the moment polytope is a wedge with edges pointing along vectors $(1, 0), (n, a)$, as seen in figure 4. $A(n, a)$ has a almost complex structure J coming from the canonical complex structure on $\mathbb{C}^2$.

We have the commutative diagram

$$\begin{tikzcd} \mathbb{C}^2 \arrow[r] \arrow[d, "\mathrm{H}"] & A(n,a) \arrow[d, "\mathrm{G}"] \\ \Delta_{\mathbb{C}^2} \arrow[r] & \Delta_{A(n,a)} \end{tikzcd}$$

After mutation the moment image of B_{dpq} looks as in figure 5. Removing the preimage of the branch cut line $\mu^{-1}(l)$ marked in red in figure 5, the moment image is the same as that of $A(dp^2, dpq - 1)$ with the corresponding line removed. Since the moment images are the same, by Delzant we get a symplectic embedding

$$B_{dpq} \setminus \mu^{-1}(l) \to A(dp^2, dpq - 1),$$

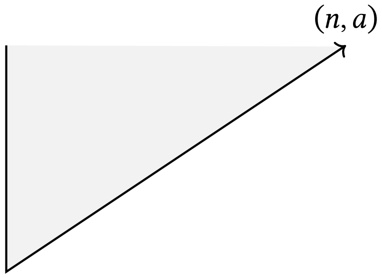


Figure 4: Moment image of $A(n, a)$ with given by Hamiltonian system G

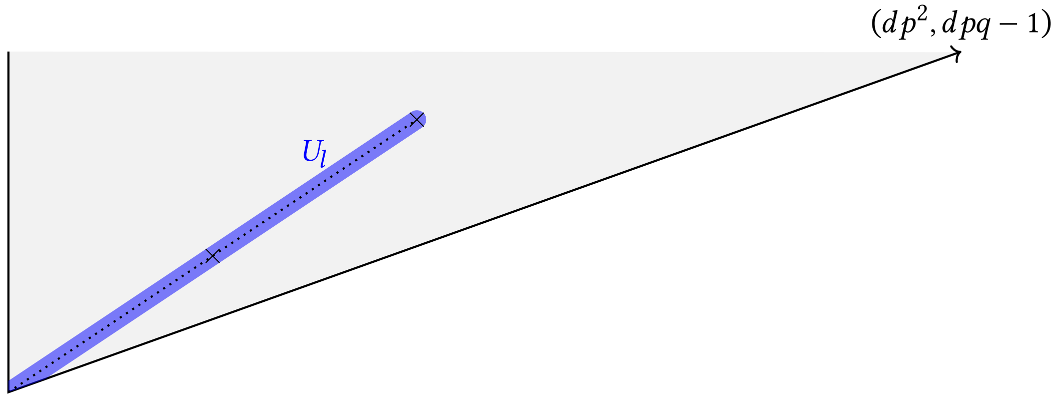


Figure 5: Moment image of B_{dpq} after mutation

and we can equip B_{dpq} with a almost complex structure J obtained by extending the almost complex structure of $A(dp^2, dpq - 1)$ to $\mu^{-1}(l)$.

Lemma 4.3. *Equipped with this almost complex structure we have*

$$\min\{\sigma_D(B_{dpq}, L(x_0, y_0), J), \sigma_S(B_{dpq}, J)\} = x_0.$$

Proof. Independently of the choice of J, there are no J-holomorphic spheres in B_{dpq}, since $H_2(B_{dpq})$ admits a basis the elements of which can be realized by Lagrangian spheres as discussed in section 3.

In order to deal with disks we choose a particular J as follows. Perform nodal slides such that all nodes lie in $\{x > x_0 + \varepsilon\}$. The subset $U = \pi^{-1}(\{x < x_0 + \varepsilon\})$ is symplectomorphic to $D(x_0 + \varepsilon) \times T^*S^1$. Take the standard complex structure coming from this symplectomorphism on U and extend it to an arbitrary almost complex structure J taming ω. Since the projection

$$p\colon (U, J|_U) \to (D(x_0 + \varepsilon), i)$$

is holomorphic, the maximum principle implies that the image of any J-disk with boundary on $T(x_0, y_0)$ is contained in U. Since $H_2(U, T(x_0, y_0))$ is generated by the disk D_0 (see section 3), and since there is an obvious J-disk u with $[u] = D_0$, the claim follows. $\square$

gibts hierfür noch eine referenz? Weil als armen Studenten würde mich sowas aufregen. Ich bin vom Wort allein noch nicht ganz überzeugt...

Add proof of theorem 1.2.

4.2 D_0 stays a Minimal J-Disks for Suitable Embeddings

Let $B(a) \in \mathbb{C}^n$ be the open ball in $\mathbb{C}^n$ of radius $\sqrt{\frac{a}{\pi}}$. In [2, appendix A] the following lemma is proven:

Lemma 4.4. *Let $a_+ > a_- \geq 0$. Let $u\colon \Sigma \to B(a_+) \setminus \overline{B(a_-)}$ be a J-holomorphic curve such that the closure of $u(\Sigma)$ in $\mathbb{C}^n$ intersects $\partial B(a_-)$. Then $\int_u \omega \geq a_+ - a_-$.*

We give the slight generalization:

Lemma 4.5. *Let $a_+ > a_- > 0$, and*

$$X = \mathbf{G}^{-1}(\{c_1(0,1) + c_2(n,a) \mid a_- < c_1 + c_2 < a_+\}) \subset A(n,a)\ ,$$

equipped with the almost complex structure of $A(n,a)$.

Let $u\colon \Sigma \to X$ be a J-holomorphic curve whose closure intersects

$$\mathbf{H}^{-1}(\{c_1(0,1) + c_2(n,a) \mid a_- = c_1 + c_2\})\ .$$

Then $\int_u \omega \geq a_+ - a_-$.

Remark 4.6. Suppose we have a moment polytope Δ of a (almost) toric symplectic manifold or orbifold $\mathbf{H}\colon M \to \Delta$ with two non-parallel edges given by the two primitive vectors u_1, u_2, as in figure 6. Suppose without loss of generality that the edges intersect in the origin. Then the subset

$$X = \mathbf{H}^{-1}(\{c_1u_1 + c_2u_2 \mid a_- < c_1 + c_2 < a_+\})$$

with $a_\pm$ such that $a_\pm u_1, a_\pm u_2 \in \Delta$, can be transformed by a $T \in \mathrm{GL}(\mathbb{Z}^2)$, such that $Tu_1 = (0,1), Tu_2 = (n,a)$, for some coprime integers n, a.

With this transformation we can view X as a subset of $A(n,a)$. Equipping M with an extension of the almost complex structure coming from $A(n,a)$, we get that J-curves in M intersecting

$$\mathbf{H}^{-1}(\{c_1u_1 + c_2u_2 \mid a_- = c_1 + c_2\})$$

must have at least area $a_+ - a_-$.

Proof. Since the action of μ_n is free in $(\mathbb{C}^*)^2$, the projection map $\pi\colon (\mathbb{C}^*)^2 \to A(n,a) \setminus \{[(0,0)]\}$ is an n-fold covering map.

As shown below, the preimage $\pi^{-1}(X)$ is $B(na_+) \setminus \overline{B(na_-)}$, and u lifts to a J-curve $\tilde{u}$, i.e. a curve making the diagram

$$\begin{array}{ccc} \Sigma' & \xrightarrow{\tilde{u}} & \mathbb{C}^2 \\ \downarrow{\scriptstyle\tilde{\pi}} & & \downarrow{\scriptstyle\pi} \\ \Sigma & \xrightarrow{u} & A(n,a) \end{array}$$

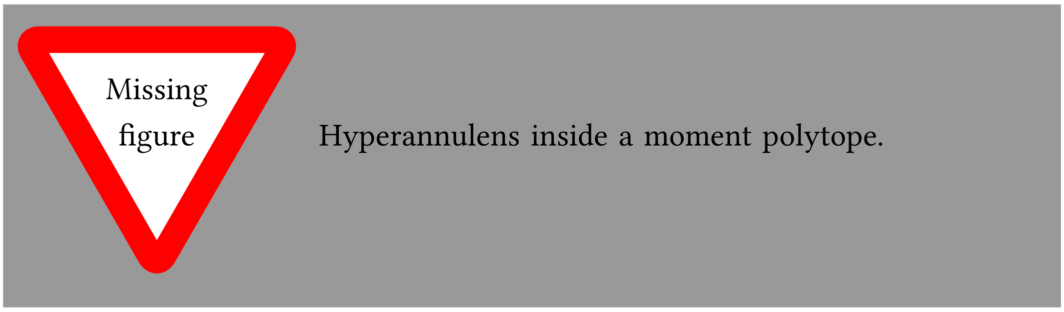


Figure 6: Hyperannulens inside a moment polytope.

NOOOOOOOOOOOO!

commute, where $\tilde{\pi} : \Sigma' \to \Sigma$ is some n-fold covering of Σ.

Using lemma 4.4, we get that the symplectic area of $\tilde{u}$ is at least $n(a_+ - a_-)$, and since $\tilde{u}$ is an n-fold covering of u, u has at least symplectic area $a_+ - a_-$, as desired.

To show that $\pi^{-1}(X) = B(na_+) \setminus \overline{B(na_-)}$, note that the Hamiltonian system $\mathbf{G}$ from equation (1), is given by a linear transformation of the standard system on $\mathbb{C}^2$

$$\mathbf{H}(z_1, z_2) = \frac{1}{2}\left(|z_1|^2, |z_2|^2\right),$$

given by the matrix

$$\begin{pmatrix} 0 & 1 \\ \frac{1}{n} & \frac{a}{n} \end{pmatrix},$$

Das ist jetzt nicht wie bei Evans linkswirkend, sondern normal...

whose inverse maps $\mathbf{G}(X)$ to $\mathbf{H}(B(na_+) \setminus \overline{B(na_-)})$, and since π maps fibres to fibres, the claim follows. $\square$

Define $B_{dpq}(a) := \mathbf{G}^{-1}\{c_1(0,1) + c_2(dp^2, dpq - 1) \mid c_1 + c_2 < a\}$, and let (X, ω, J) be a symplectic manifold with tame almost complex structure.

was ist G genau?

gibts davon noch eine schönere definition?

Suppose we have an embedding $B_{dqp}(2a) \to X$, and that all J-spheres in X have at least area a. Using remark 4.6 and lemma 4.5, we get that the minimal J-curve with boundary on the torus $T_k(a)$ has area a, and since there are no smaller J-spheres by assumption, using theorem 4.1, we get that the displacement energy of $T_k(a)$ is at least a.

Brauchen wir hier noch ein ε platz?

References

[1] Yu. V. Chekanov. “Lagrangian intersections, symplectic energy, and areas of holomorphic curves”. In: *Duke Mathematical Journal* 95 (1998), pp. 213–226.

[2] Yu. V. Chekanov and Felix Schlenk. “Lagrangian product tori in tame symplectic manifolds”. In: *arXiv: Symplectic Geometry* (2015).

[3] Jonathan David Evans. *Lectures on Lagrangian torus fibrations.* 2021. DOI: 10.48550/ARXIV.2110.08643. URL: https://arxiv.org/abs/2110.08643.