

# A REMARK ON DEFORMATION OF GROMOV NON-SQUEEZING

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**ABSTRACT.** We prove that in dimension 4 the Gromov non-squeezing phenomenon is persistent with respect to  $C^0$  symplectic perturbations of the symplectic form on the range. Given such a perturbation, we can no longer compactify the range and hence the classical Gromov argument breaks down. Our methods consist of a certain trap idea for holomorphic curves, analogous to traps in dynamical systems, and Hofer-Wysocki-Zehnder polyfold regularization in Gromov-Witten theory, especially as recently worked out in this present context by the team of Franziska Beckschulte, Ipsita Datta, Irene Seifert, Anna-Maria Vocke, and Katrin Wehrheim. The theorem motivates an intriguing question on further deforming non-squeezing to general nearby forms.

## 1. INTRODUCTION

One of the most important to this day results in symplectic geometry is the so called Gromov non-squeezing theorem, appearing in the seminal paper of Gromov [3]. Let  $\omega_{st} = \sum_{i=1}^n dp_i \wedge dq_i$  denote the standard symplectic form on  $\mathbb{R}^{2n}$ . Gromov's theorem then says that there does not exist a symplectic embedding

$$(B_R, \omega_{st}) \hookrightarrow (S^2 \times \mathbb{R}^{2n-2}, \omega_{\pi r^2} \oplus \omega_{st}),$$

for  $R > r$ , with  $B_R$  the standard closed radius  $R$  ball in  $\mathbb{R}^{2n}$  centered at 0, and  $\omega_{\pi r^2}$  a symplectic form on  $S^2$  with area  $\pi r^2$ .

We show that in dimension 4 Gromov's non-squeezing is  $C^0$  persistent in the following sense.

**Theorem 1.1.** *Let  $R > r > 0$  be given, and let  $\omega = \omega_{\pi r^2} \oplus \omega_{st}$  be the symplectic form on  $M = S^2 \times \mathbb{R}^2$  as above. Then there is an  $\epsilon > 0$  s.t. for any symplectic form  $\omega'$  on  $M$ ,  $C^0$   $\epsilon$ -close to  $\omega$ , there is no symplectic embedding  $\phi : (B_R, \omega_{st}) \hookrightarrow (M, \omega')$ , meaning that  $\phi^* \omega' = \omega_{st}$ .*

To prove this, we cannot use the classical Gromov-Witten argument since we cannot compactify the range. Another idea is needed to get an appropriate compact moduli space of holomorphic curves. For the moment we are forced to restrict to dimension 4, where we construct a certain holomorphic trap (Definition 2.1) somewhat analogous to traps in dynamical systems. For regularization we then use the polyfold setup as already worked in a close context in [1].

It is natural to ask if the above theorem continues to hold for general nearby forms. Or formally this translates to:

*Question 1.* Let  $R > r > 0$  be given, and let  $\omega = \omega_{\pi r^2} \oplus \omega_{st}$  be the symplectic form on  $M = S^2 \times \mathbb{R}^{2n-2}$ , as above. For every  $\epsilon > 0$  is there a 2-form  $\omega'$  on  $M$ ,  $C^0$   $\epsilon$ -close to  $\omega$ , such that there is a symplectic embedding  $\phi : B_R \hookrightarrow M$ , i.e. s.t.  $\phi^* \omega' = \omega_{st}$ ? Note that if  $\omega'$  as above exists, it cannot be globally closed (for  $\epsilon$  sufficiently small) by the theorem above.

We cannot readily reduce this question to just applying Theorem 1.1 (in dimension 4). This is because, while a symplectic form on a subdomain of the form  $\phi(B_R) \subset M$  extends to a symplectic form, by a classical theorem of Gromov [2], the extension may not be  $C^0$  close to  $\omega$ . Indeed, this appears to be rather unlikely to happen, unless there exists a stronger type of h-principle than Gromov's which allows us to control the uniform norm.

The above question seems to be difficult. My opinion is that the answer is 'yes', in part because it is difficult to imagine any obstruction, for example we no longer have Gromov-Witten theory for

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general  $\omega'$ . On the other hand, my attempts to construct an example failed, so that ‘no’ is certainly very possible.

A work of Müller [6] explores a different kind of question, by instead relaxing the condition of the map being symplectic. This is a very different idea, and there is no direct connection to our problem, as pull-backs by diffeomorphisms of nearby forms may not be nearby. Hence, there is no way to go from nearby embeddings that we work with to  $\epsilon$ -symplectic embeddings of Müller.

## 2. A TRAP FOR HOLOMORPHIC CURVES

For basic notions of  $J$ -holomorphic curves we refer the reader to [5].

**Definition 2.1.** *Let  $(M, J)$  be an almost complex manifold, and  $A \in H_2(M)$  fixed. Let  $K \subset M$  be a closed subset. Suppose that for every  $x \in \partial K$  (the topological boundary) there is a  $J$ -holomorphic (real codimension 2) compact hyperplane  $H_x \ni x$  satisfying:*

- $H_x \subset K$ .
- $A \cdot H_x \leq 0$ , where the left-hand side is the homological intersection number.

We call such a  $K$  a  **$J$ -holomorphic trap** (for class  $A$  curves).

**Lemma 2.2.** *Let  $M, J$  and  $A$  be as above, and  $K$  be a  $J$ -holomorphic trap for class  $A$  curves. Let  $u : \Sigma \rightarrow M$  be a  $J$ -holomorphic class  $A$  curve  $u$  with  $\Sigma$  a connected closed Riemann surface. Then*

$$\text{image } u \cap K \neq \emptyset \implies \text{image } u \subset K.$$

*Proof.* Suppose that  $u$  intersects  $\partial K$ , otherwise we already have  $\text{image } u \subset \text{interior}(K)$ , since  $\text{image } u$  is connected (and by elementary topology). Then  $u$  intersects  $H_x$  as in the definition of a holomorphic trap, for some  $x$ . Consequently, as  $A \cdot H_x \leq 0$ , by positivity of intersections [5, Section 2.6],  $\text{image } u \subset H_x \subset K$ .  $\square$

## 3. PROOF OF THEOREM 1.1

**Definition 3.1.** *We say that a pair  $(\omega, J)$  of a 2-form  $\omega$  on a smooth manifold  $M$  and an almost complex structure  $J$  on  $M$  are **compatible** if  $\omega(\cdot, J\cdot)$  defines a  $J$ -invariant inner product  $g_{\omega, J}$  on  $M$ .*

Let us quickly recall the definition of the  $C^0$  distance  $d_{C^0}$ , on the set of 2-forms  $\Omega^2(M)$  for a fixed metric  $g$  on  $M$ .

$$d_{C^0}(\omega_0, \omega_1) = \sup_{|v \wedge w|_g = 1} |\omega_0(v, w) - \omega_1(v, w)|,$$

where more specifically, the supremum is over all  $g$ -norm 1 simple bivectors  $v \wedge w$  in  $\Lambda^2(TM)$ .

Let  $\omega$  be the symplectic form on  $M = S^2 \times \mathbb{R}^2$  as in the statement. In our case  $d_{C^0}$  will be defined with respect to the metric  $g_{\omega, J}$  as in Definition 3.1 for  $J$  the standard product complex structure.

Suppose by contradiction that for every  $\epsilon > 0$  there is an  $\omega_1$  s.t.  $d_{C^0}(\omega, \omega_1) < \epsilon$  and such that there exists a symplectic embedding

$$\phi : B_R \hookrightarrow (M, \omega_1).$$

Let  $\epsilon' > 0$  be s.t. any symplectic form  $\omega_1$  on  $M$ ,  $C^0$   $\epsilon'$ -close to  $\omega$  satisfies:

- $\omega_t = (1 - t)\omega + t\omega_1$  is non-degenerate, for each  $t \in [0, 1]$ .
- For each  $t \in [0, 1]$ ,  $\omega_t$  is non-degenerate on all the fibers of the natural projection  $p : (M = S^2 \times \mathbb{R}^2) \rightarrow \mathbb{R}^2$ . In what follows we just call them **fibers**.

For  $\epsilon < \epsilon'$  as above, let  $\omega_1$  and  $\phi : B_R \rightarrow (M, \omega_1)$  be as in our hypothesis. Set  $B := \phi(B_R)$  and let  $D \supset B$  be an open domain, with compact closure  $K$ , s.t.  $K$  is the product  $S^2 \times D^2$  for  $D^2 \subset \mathbb{R}^2$  a closed disk. In particular,  $\partial K$  is smoothly foliated by the fibers. We denote by  $T^{\text{vert}} \partial K \subset TM$ , the sub-bundle of vectors tangent to the leaves of the above-mentioned foliation.

We may extend  $\phi_* j$  to an  $\omega_1$ -compatible almost complex structure  $J_1$  on  $M$ , preserving  $T^{\text{vert}} \partial K$  using:

- $\text{image } \phi$  does not intersect  $\partial K$ .
- The non-degeneracy of  $\omega_1$  on the fibers, which follows by the defining condition of  $\epsilon$ .

- The well known existence/flexibility results for compatible almost complex structures on symplectic vector bundles.

We may then extend  $J_1$  to a family  $\{J_t\}$ ,  $t \in [0, 1]$ , of almost complex structures on  $M$ , s.t.  $J_t$  is  $\omega_t$ -compatible for each  $t$ , with  $J_0 = J$  as above, and such that  $J_t$  preserves  $T^{vert}\partial K$  for each  $t$ . The latter condition can be satisfied by similar reasoning as above, using that  $\omega_t$  is non-degenerate on the fibers for each  $t$ .

So the fibers above are  $J_t$ -holomorphic hyperplanes for each  $t$ , and smoothly foliate  $\partial K$ . Moreover, if  $A = [S^2] \otimes [pt]$  is as in the statement, then the intersection number of  $A$  with a fiber is 0. That is  $A \cdot p^{-1}(z) = 0$ , for  $\forall z \in \mathbb{R}^2$ . And so  $K$  is a compact  $J_t$ -holomorphic trap for class  $A$  curves, for each  $t$ .

Set  $x_0 := \phi(0)$ . Denote by  $\mathcal{M}_t$  the space of equivalence classes of maps  $u : \mathbb{CP}^1 \rightarrow M$ , where  $u$  is a  $J_t$ -holomorphic, class  $A$  curve passing through  $x_0$ . The equivalence relation is by the usual biholomorphism reparametrization group action, so that  $u \sim u'$  if there exists a biholomorphism  $\phi : \mathbb{CP}^1 \rightarrow \mathbb{CP}^1$  s.t.  $u' = u \circ \phi$ . Then  $\mathcal{M} = \cup_t \mathcal{M}_t$  is compact by energy minimality of  $A$  (which rules out bubbling), by Lemma 2.2, and by compactness of  $K$ .

We need to regularize, however the evaluation map  $ev : \mathcal{E} \rightarrow M$ ,  $u \mapsto u(0)$ , is not Banach smooth, where  $\mathcal{E}$  is some standard Banach space (as in [5]) of class  $A$  (suitable regularity) curves in  $M$ . So that applying the standard Banach regularization techniques as in [5] is difficult. Note that in the classical Gromov setting, where  $M$  is compact, this is irrelevant, as we can regularize the unconstrained moduli space, and then take the homological intersection of the evaluation at a point (i.e. take the Gromov-Witten invariant). But we cannot do that here, since the unconstrained moduli space in our case is not compact.

But we may use polyfold theory. As explained in [1, Section 3.5], in a essentially identical situation, we may embed  $\mathcal{M}$  into a natural polyfold setup of Hofer-Wysocki-Zehnder [4]. The main point being that the map  $ev$  above is suitably smooth in the polyfold setting, and there is a suitable implicit function theorem for this map. More to the point, we express  $\mathcal{M}$  as the zero set of an sc-Fredholm section of a suitable (tame, strong)  $M$ -polyfold bundle. The only difference with the setup of [1, Section 3.5] is that they compactify  $M$  to  $S^2 \times T^2$ , to get a compact moduli space  $\mathcal{M}$ . We of course cannot compactify, but remember that we used the holomorphic trap idea to force compactness of  $\mathcal{M}$ . And so we are in an equivalent situation.

Again as in [1], we take the  $M$ -polyfold regularization of  $\mathcal{M}$ . This gives a one dimensional compact cobordism  $\mathcal{M}^{reg}$  between  $\mathcal{M}_0^{reg}$  and  $\mathcal{M}_1^{reg}$ .

Now  $\mathcal{M}_0^{reg}$  is a point: corresponding to the unique ( $J = J_0$ )-holomorphic class  $A$ , curve  $u : \mathbb{CP}^1 \rightarrow M$  passing through  $x_0$ . Consequently,  $\mathcal{M}_1^{reg}$  is non-empty, that is there is a  $J_1$ -holomorphic class  $A$  curve  $u_0 : \mathbb{CP}^1 \rightarrow M$  passing through  $x_0$ .

Now we have:

$$|\langle \omega_1, A \rangle - \pi \cdot r^2| = |\langle \omega_1, A \rangle - \langle \omega, A \rangle| \leq \epsilon \pi \cdot r^2,$$

as  $\langle \omega, A \rangle = \pi r^2$ , and as  $d_{C^0}(\omega, \omega_1) < \epsilon$ , (also using that we can find a representative for  $A$  whose  $g$ -area is  $\pi r^2$ ). So choosing  $\epsilon$  appropriately we get

$$\left| \int_{\mathbb{CP}^1} u_0^* \omega_1 - \pi r^2 \right| < \pi R^2 - \pi r^2,$$

And consequently,

$$\int_{\mathbb{CP}^1} u_0^* \omega_1 < \pi R^2.$$

We may then proceed exactly as in the now classical proof of Gromov [3] of the non-squeezing theorem to get a contradiction and finish the proof. A bit more specifically,  $\phi^{-1}(\text{image } \phi \cap \text{image } u_0)$  is a minimal surface in  $B_R$ , with boundary on the boundary of  $B_R$ , and passing through  $0 \in B_R$ . By construction it has area strictly less than  $\pi R^2$ , which is impossible by the classical monotonicity theorem of differential geometry. See also [1] where the monotonicity theorem is suitably generalized, to better fit the present context.  $\square$

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