STABILITY IS NOT OPEN

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ABSTRACT. We give an example of a symplectic manifold with a stable hypersurface such that nearby hypersurfaces are typically unstable.

1. INTRODUCTION

A closed hypersurface Σ in a symplectic manifold (M, Ω) is called *stable* if a neighbourhood of Σ can be foliated by hypersurfaces whose characteristic foliations are conjugate. Here the characteristic foliation on a hypersurface Σ is defined by the 1-dimensional distribution $\ker(\Omega|_\Sigma)$. Stability was introduced in [12] as a condition on hypersurfaces for which the Weinstein conjecture can be proved. More recently, it has attained importance as the condition needed for the compactness results underlying Symplectic Field Theory [7, 2, 5] and Rabinowitz Floer homology [3, 4].

Let us consider, in a fixed symplectic manifold (M, Ω), the space $\mathcal{HS}$ of closed hypersurfaces equipped with the C^∞-topology and its subset $\mathcal{SHS}$ of stable hypersurfaces. It is easy to see that $\mathcal{SHS}$ is not closed: For example, the horocycle flow on a hyperbolic surface defines a hypersurface which is unstable but the smooth limit of stable ones; see [4] for many more examples. On the other hand, $\mathcal{SHS}$ contains open components, e.g. those corresponding to hypersurfaces of contact type. This prompted the question whether the set $\mathcal{SHS}$ is actually open in $\mathcal{HS}$. The result of this paper shows that this is not the case.

Theorem 1.1. *There exists a stable closed hypersurface Σ in a symplectic 6-manifold such that nearby hypersurfaces are typically unstable in the following sense: There exists a neighbourhood of Σ in $\mathcal{HS}$ which contains an open dense set consisting of unstable hypersurfaces.*

The theorem continues to hold if the C^∞ topology is replaced by the C^k topology for some $k \geq 2$ and hypersurfaces are only assumed to be of class C^k.

The theorem can be rephrased in terms of *stable Hamiltonian structures* [2, 5, 6]. A two-form ω on an odd-dimensional manifold Σ is called a *Hamiltonian structure* if it is closed and maximally nondegenerate in the sense that its kernel distribution is one-dimensional. It is called *stable* if there exists a one-form λ such that $\lambda|_{\ker \omega} \neq 0$ and $\ker \omega \subset \ker d\lambda$. Then a hypersurface Σ in a symplectic manifold (M, Ω) is stable iff $\Omega|_\Sigma$ defines a stable Hamiltonian structure, and every stable Hamiltonian structure arises as a stable hypersurface in some symplectic manifold [5]. Now Theorem 1.1 can be rephrased as follows: *There exists a stable Hamiltonian structure ω on a closed*

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5-manifold Σ such that nearby Hamiltonian structures with the same cohomology class as ω are typically unstable.

Theorem 1.1 has implications on the foundations of holomorphic curve theories such as Symplectic Field Theory [7, 2, 5] and Rabinowitz Floer homology [3, 4]. For the construction of those theories one needs to perturb a given stable Hamiltonian structure to make all closed characteristics nondegenerate. Theorem 1.1 suggests that such a perturbation may not be possible within the class of stable Hamiltonian structures (see also [6] for a result pointing in the same direction). In Rabinowitz Floer homology this problem can be overcome in the following way [4]: One chooses an additional Hamiltonian perturbation of the Rabinowitz action functional. For a generic small perturbation the Rabinowitz action functional becomes Morse, but for the perturbed action functional one might lose compactness. However, one can still define a boundary operator by taking into account only gradient flow lines close to the original ones. We wonder if a similar strategy can be applied to SFT as well.

2. Preliminaries on Anosov Hamiltonian structures

Anosov Hamiltonian structures. Recall that the flow ϕ_t of a vector field F on a closed manifold Σ is *Anosov* if there is a splitting $T\Sigma = \mathbb{R}F \oplus E^s \oplus E^u$ and positive constants λ and C such that for all $x \in \Sigma$

$$|d_x\phi_t(v)| \leq Ce^{-\lambda t}|v| \quad \text{for } v \in E^s \text{ and } t \geq 0,$$

$$|d_x\phi_{-t}(v)| \leq Ce^{-\lambda t}|v| \quad \text{for } v \in E^u \text{ and } t \geq 0.$$

If an Anosov vector field F is rescaled by a positive function its flow remains Anosov [1, 15]. It will be useful for us to know how the bundles E^s and E^u change when we rescale F by a smooth positive function $r : \Sigma \to \mathbb{R}_+$. Let $\tilde{\phi}$ be the flow of rF and $\tilde{E}^s$ its stable bundle. Then (cf. [15])

$$\tilde{E}^s(x) = \{v + z(x,v)F(x) : \quad v \in E^s(x)\}, \tag{1}$$

where $z(x, v)$ is a continuous 1-form (i.e. linear in v and continuous in x). Moreover, if we let $l = l(t, x)$ be (for fixed x) the inverse of the diffeomorphism

$$t \mapsto \int_0^t r(\phi_s(x))^{-1}\, ds$$

then

$$d\tilde{\phi}_t(v + z(x,v)F(x)) = d\phi_l(v) + z(\phi_l(v), d\phi_l(v))F(\phi_l(x)). \tag{2}$$

This shows that for closed Σ the flow $\tilde{\phi}_t$ is again Anosov. There is a similar expression for $\tilde{E}^u$. It is clear from the discussion above that the weak bundles $\mathbb{R}F \oplus E^s$ and $\mathbb{R}F \oplus E^u$ do not change under rescaling of F (the strong bundles $E^{s,u}$ are indeed affected by rescaling as we have just seen).

Let (Σ, ω) be a Hamiltonian structure. We say that the structure is *Anosov* if the flow of any vector field F spanning $\ker \omega$ is Anosov.

We say that an Anosov Hamiltonian structure satisfies the 1/2-*pinching condition* or that it is *1-bunched* [9, 10] if for any vector field F spanning $\ker\omega$ with flow ϕ_t there are functions $\mu_f, \mu_s : \Sigma \times \mathbb{R}_+ \to \mathbb{R}_+$ such that

- $\lim_{t\to\infty} \sup_{x\in\Sigma} \frac{\mu_s(x,t)^2}{\mu_f(x,t)} = 0$;
- $\mu_f(x,t)|v| \le |d\phi_t(v)| \le \mu_s(x,t)|v|$ for all $x \in \Sigma$, $t > 0$ and $v \in E^s(x)$, and $\mu_f(x,t)|v| \le |d\phi_{-t}(v)| \le \mu_s(x,t)|v|$ for all $x \in \Sigma$, $t > 0$ and $v \in E^u(\phi_t x)$.

We remark that the 1/2-pinching condition is invariant under rescaling. Indeed, consider the flow $\tilde{\phi}_t$ of rF. It is clear from (1) and (2) that there is a positive constant κ such that

$$\frac{1}{\kappa}\mu_f(x, l(t,x))|\tilde{v}| \le |d\tilde{\phi}_t(\tilde{v})| \le \kappa\mu_s(x, l(t,x))|\tilde{v}|$$

for $t > 0$ and $\tilde{v} \in \tilde{E}^s$ (with a similar expression for $\tilde{E}^u$). We know that given $\varepsilon > 0$, there exists $T > 0$ such that for all $x \in \Sigma$ and all $t > T$ we have

$$\frac{\mu_s(x,t)^2}{\mu_f(x,t)} < \varepsilon.$$

On the other hand, there exists $a > 0$ such that $l(t,x) \ge at$ for all $x \in \Sigma$ and $t > 0$. Hence, if we choose $t > T/a$ we have

$$\frac{\mu_s(x, l(t,x))^2}{\mu_f(x, l(t,x))} < \varepsilon$$

for all $x \in \Sigma$. Therefore

$$\lim_{t\to\infty} \sup_{x\in\Sigma} \frac{\mu_s(x, l(t,x))^2}{\mu_f(x, l(t,x))} = 0$$

and thus $\tilde{\phi}_t$ is also 1/2-pinched.

Hence the Anosov property as well as the 1/2-pinching condition are invariant under rescaling and thus intrinsic properties of the Hamiltonian structure. One of the main consequences of the 1/2-pinching condition is that the weak bundles $\mathbb{R}F \oplus E^s$ and $\mathbb{R}F \oplus E^u$ are of class C^1 [10, Theorem 5] (see also [11]).

Stable Anosov Hamiltonian structures. Suppose now (Σ, ω) is a *stable* Anosov Hamiltonian structure satisfying the 1/2-pinching condition. Let λ be a stabilizing 1-form and R the Reeb vector field defined by $i_R\omega = \lambda_0$ and $\lambda(R) = 1$. Invariance under the flow implies that ω and λ both vanish on E^s and E^u. Since the flow ϕ_t of R is Anosov and $E^s \oplus E^u = \ker\lambda$ which is C^∞, it follows that $E^s = \ker\lambda \cap (\mathbb{R}F \oplus E^s)$ and E^u must be C^1. Under these conditions we can introduce the *Kanai connection* [13] which is defined as follows.

Let I be the $(1,1)$-tensor on Σ given by $I(v) = -v$ for $v \in E^s$, $I(v) = v$ for $v \in E^u$ and $I(R) = 0$. Consider the symmetric non-degenerate bilinear form given by

$$h(X,Y) := \omega(X, IY) + \lambda \otimes \lambda(X,Y).$$

The pseudo-Riemannian metric h is of class C^1 and thus there exists a unique C^0 affine connection ∇ such that:

(1) h is parallel with respect to ∇;

(2) ∇ has torsion $\omega \otimes R$.

This connection has the following desirable properties [8, 13]: it is invariant under ϕ_t and the Anosov splitting is invariant under ∇: if X is any section of $E^{s,u}$, $\nabla_v X \in E^{s,u}$ for any v.

The other good consequence of the 1/2-pinching condition, besides C^1 smoothness of the bundles, is the following lemma (cf. [13, Lemma 3.2]).

Lemma 2.1. $\nabla(d\lambda) = 0$.

Proof. Suppose τ is any invariant $(0,3)$-tensor annihilated by R. We claim that τ must vanish. To see this, consider for example a triple of vectors (v_1, v_2, v_3) where $v_1, v_2 \in E^s$ but $v_3 \in E^u$. Then there is a constant $C > 0$ such that for all $t \geq 0$

$$\begin{aligned} |\tau_x(v_1, v_2, v_3)| &= |\tau_{\phi_t x}(d\phi_t(v_1), d\phi_t(v_2), d\phi_t(v_3))| \\ &\leq C\mu_s(x,t)^2 \mu_f(x,t)^{-1} |v_1||v_2||v_3|. \end{aligned}$$

By the 1/2-pinching condition the last expression tends to zero as $t \to \infty$ and therefore $\tau_x(v_1, v_2, v_3) = 0$. The same will happen for other possible triples (v_1, v_2, v_3) when we let $t \to \pm\infty$.

Since $d\lambda$ and ∇ are ϕ_t-invariant, so is $\nabla(d\lambda)$. Since $i_R d\lambda = 0$, $\nabla(d\lambda)$ is also annihilated by R (to see that $\nabla_R(d\lambda) = 0$ use that $d\lambda$ is ϕ_t-invariant and that $\nabla_R = L_R$). Hence by the previous argument applied to $\tau = \nabla(d\lambda)$ we conclude that $\nabla(d\lambda) = 0$ as desired. ☐

Quasi-conformal Anosov Hamiltonian structures. Let ϕ_t be an Anosov flow on Σ endowed with a C^0-Riemannian metric. Consider the following functions on $\Sigma \times \mathbb{R}$:

$$K^s(x,t) = \frac{\max\{|d\phi_t(v)| : \; v \in E^s(x), \; |v| = 1\}}{\min\{|d\phi_t(v)| : \; v \in E^s(x), \; |v| = 1\}},$$

$$K^u(x,t) = \frac{\max\{|d\phi_t(v)| : \; v \in E^u(x), \; |v| = 1\}}{\min\{|d\phi_t(v)| : \; v \in E^u(x), \; |v| = 1\}}.$$

The flow ϕ_t is said to be *quasi-conformal* if K^u and K^s are both bounded on $\Sigma \times \mathbb{R}$. This property is clearly independent of the choice of Riemannian metric used to define K^s and K^u. Moreover it is shown in [18, Proposition 3.5] that quasi-conformality is independent of times changes, thus it makes sense to talk about quasi-conformal Anosov Hamiltonian structures. The next theorem will be useful for us.

Theorem 2.2 ([18], Theorems 1.3 and 1.4)**.** *Let ϕ_t be a topologically mixing Anosov flow with $\dim E^s \geq 2$ and $\dim E^u \geq 2$. If ϕ_t is quasi-conformal, then the weak bundles are C^∞.*

Recall that ϕ_t is topologically mixing if for any two nonempty open sets U and V in Σ, there is a compact set $K \subset \mathbb{R}$ such that for every $t \in \mathbb{R} \setminus K$ we have $\phi_t(U) \cap V \neq \emptyset$. Recall also that ϕ_t is said to be transitive if there is a dense orbit. Our Anosov flows will always be transitive since they preserve a smooth volume form [14, Chapter 18].

3. A theorem

Theorem 3.1. *Let (Σ, ω) be a 1/2-pinched Anosov Hamiltonian structure with $[\omega] \neq 0$, but $[\omega^2] = 0$. Suppose in addition that Σ fibres over a closed 3-manifold with fibres diffeomorphic to S^2 and transversal to the weak subbundles. Then, if (Σ, ω) is stable, the weak subbundles must be C^∞.*

Proof. The proof of this theorem is very much inspired by the proof of Theorem 2 in [13]. We first make the following observation:

- E^s (E^u) cannot contain a nontrivial proper continuous subbundle.

Indeed since $\mathbb{R}R \oplus E^u$ is transversal to the fibres of the fibration $\Sigma \to M$ by 2-spheres, we can write $T\Sigma = V \oplus \mathbb{R}R \oplus E^u$ where V is the vertical subbundle of the fibration. Using this splitting we may define an isomorphism $E^s \mapsto V$ and since the tangent bundle of S^2 does not admit a nontrivial proper continuous subbundle, the same holds for E^s (and E^u).

Next we observe that the stabilizing 1-form λ cannot be closed. Indeed, write $\omega^2 = d\tau$ and note that if λ was closed, then the volume form $\lambda \wedge d\tau$ would be exact, which is absurd.

Since ω is non-degenerate, there exists a smooth bundle map $L : E^s \oplus E^u \to E^s \oplus E^u$ such that for sections X, Y of $E^s \oplus E^u$

$$d\lambda(X, Y) = \omega(LX, Y) = \omega(X, LY).$$

The map L is invariant under ϕ_t and preserves the decomposition $E^s \oplus E^u$, i.e. $L = L^s + L^u$, where $L^s : E^s \to E^s$ and $L^u : E^u \to E^u$. In particular, L commutes with I. By Lemma 2.1, the 1/2-pinching condition implies that $\nabla(d\lambda) = 0$ and thus L is parallel with respect to ∇. Note that by transitivity of ϕ_t, the characteristic polynomial of L^s_x is independent of $x \in \Sigma$. Let $\rho \in \mathbb{C}$ be an eigenvalue of L^s. Consider $A := L^s - \Re(\rho)\mathrm{Id}$. Note that A cannot be zero: Otherwise $d\lambda = c\,\omega$ for a constant $c \in \mathbb{R}$; since λ is not closed, $c \neq 0$, which in turns implies $[\omega] = 0$, contradicting the hypotheses of the theorem.

Clearly A^2 has $\mu := -\Im(\rho)^2$ as an eigenvalue. Let $H \subset E^s$ denote the eigenspace of the eigenvalue μ. Since L^s is parallel it has the same dimension at every point $x \in \Sigma$ and since E^s cannot contain a nontrivial proper continuous subbundle, we deduce that $H = E^s$. Hence $A^2 = \mu\mathrm{Id}$. Moreover $\mu \neq 0$, otherwise $\ker A$ would be a nontrivial proper continuous subbundle of E^s. Therefore we have proved that

$$\mathbb{J}^s := \frac{1}{\Im(\rho)}(L^s - \Re(\rho)\mathrm{Id}),$$

defines a parallel almost complex structure on E^s of class C^1 invariant under ϕ_t. Similarly we obtain an almost complex structure $\mathbb{J}^u$ on E^u.

Now choose a Riemannian metric on E^s (resp. E^u) which is invariant under $\mathbb{J}^s$ (resp. $\mathbb{J}^u$). By declaring E^s, E^u and $\mathbb{R}R$ orthogonal and R with norm 1, we obtain a metric (of class C^1) on Σ such that with respect to this metric

$$\frac{\max\{|d\phi_t(v)| : \ v \in E^s(x),\ |v| = 1\}}{\min\{|d\phi_t(v)| : \ v \in E^s(x),\ |v| = 1\}} = 1,$$

for all $t \in \mathbb{R}$ and $x \in \Sigma$. This is because ϕ_t preserves $\mathbb{J}^s$ and E^s has rank two. Similarly for E^u. This shows that (Σ, ω) is a quasi-conformal Anosov Hamiltonian structure.

Finally we note that if a transitive Anosov flow is not topologically mixing, then by a theorem of J. Plante [17] it must be a suspension with constant return function. In particular, this implies that there is a closed 1-form β such that $\beta(R) > 0$. The same argument above that proved that λ cannot be closed shows that such a β cannot exist. Hence ϕ_t is topologically mixing and by Theorem 2.2 the weak bundles must C^∞. □

Remark 3.2. Note that the proof above only requires λ to be of class C^2.

4. The example

Let Γ be a discrete group of isometries of $\mathbb{H}^3$ such that $M := \Gamma \setminus \mathbb{H}^3$ is a closed orientable hyperbolic 3-manifold. We consider the geodesic flow acting on the unit sphere bundle SM and let α be the canonical contact 1-form.

The space of invariant 2-forms of the geodesic flow of $M = \Gamma \setminus \mathbb{H}^3$ has dimension two [13, Claim 3.3]. It is spanned by the 2-form $d\alpha$, where α is the canonical contact form on the unit sphere bundle SM, and the following additional 2-form ψ which we now describe. Given a unit vector $v \in T_x\mathbb{H}^3$, let $i(v) : T_x\mathbb{H}^3 \to T_x\mathbb{H}^3$ be the linear map defined by $i(v)(v) = 0$ and $i(v)$ rotates vectors in $\{v\}^\perp$ by $\pi/2$ according to the orientation of $\mathbb{H}^3$. Any vector $\xi \in T_vS\mathbb{H}^3$ can be written as $\xi = (\xi_H, \xi_V)$ with the usual identification of horizontal and vertical components (cf. [16]). Define $J_v : T_vS\mathbb{H}^3 \to T_vS\mathbb{H}^3$ as

$$J_v(\xi_H, \xi_V) = (i(v)\xi_V, i(v)\xi_H). \tag{3}$$

Then

$$\psi_v(\xi, \eta) := d\alpha_v(J_v\xi, \eta) = \langle i(v)\xi_V, \eta_V\rangle - \langle i(v)\xi_H, \eta_H\rangle. \tag{4}$$

Clearly this construction descends to SM where we use the same notation (ψ, α, etc.) In a moment we will check that ψ is invariant under ϕ_t, but before we do so, let us describe the stable and unstable bundles of ϕ_t and the action of $d\phi_t$ on them. Recall that $d\phi_t(\xi_H, \xi_V) = (Y(t), \dot{Y}(t))$ where Y is the unique Jacobi field (along the geodesic $\pi\phi_t(v)$, where $\pi : SM \to M$ is foot-point projection) with initial conditions (ξ_H, ξ_V). Solving the Jacobi equation $\ddot{Y} - Y = 0$ we find:

$$E^s(v) = \{(w, -w) : \ w \perp v\},$$
$$E^u(v) = \{(w, w) : \ w \perp v\}.$$

Note that J leaves E^s and E^u invariant. Moreover

$$d\phi_t(w, -w) = e^{-t}(e_w(t), -e_w(t)),$$
$$d\phi_t(w, w) = e^{t}(e_w(t), e_w(t)),$$

where $e_w(t)$ is the parallel transport of w along the geodesic $\pi\phi_t(v)$. Since $e_{i(v)w}(t) = i(\pi\phi_t v)e_w(t)$ we see that $d\phi_t$ preserves J. Since $d\alpha$ is also ϕ_t invariant, it follows that ψ is invariant. Note that $i_R\psi = 0$ for the Reeb vector field R of α.

Lemma 4.1. *The invariant 2-form ψ is closed but not exact. The 4-form ψ^2 is exact and (SM, ψ) is a stable Hamiltonian structure with stabilizing 1-form α and Reeb vector field R.*

Proof. The 3-form $d\psi$ is invariant under ϕ_t and is annihilated by R. Then the proof of Lemma 2.1 shows that $d\psi = 0$ (obviously ϕ_t is 1/2-pinched). In order to show that $[\psi] \neq 0$, consider S_x the 2-sphere of unit vectors in $T_x\mathbb{H}^3$. A tangent vector $\xi \in T_vS_x$ has the form $\xi = (0, w)$ where $w \perp v$. If we take two tangent vectors $\xi = (0, w)$, $\eta = (0, u) \in T_vS_x$, from (3) and (4) we see that

$$\psi_v(\xi, \eta) = \langle i(v)w, u\rangle.$$

This implies that

$$\int_{S_x} \psi \neq 0$$

and thus $[\psi] \neq 0$. Consider now the invariant 4-form ψ^2 and the invariant 5-form $\alpha\wedge\psi^2$. By transitivity, there is a constant k such that $\alpha\wedge\psi^2 = k\,\alpha\wedge(d\alpha)^2$. Contracting with R we see that ψ^2 must be $k\,(d\alpha)^2$ and therefore exact. Finally, it is immediate from the definition (4) of ψ that its restriction to $E^s \oplus E^u = \ker\alpha$ is non-degenerate. Hence (SM, ψ) is a Hamiltonian structure with stabilizing 1-form α and Reeb vector field R. $\square$

Now let $X := SM \times (-\varepsilon, \varepsilon)$ and $\tau : X \to SM$ the obvious projection. Define $\omega_X := d(r\tau^*\alpha) + \tau^*\psi$, where $r \in (-\varepsilon, \varepsilon)$. For ε small enough (X, ω_X) is a symplectic manifold and $r = 0$ is the stable hypersurface (SM, ψ).

We have now come to our main result which implies Theorem 1.1 in the introduction.

Theorem 4.2. *A typical hypersurface $\Sigma \subset X$ near SM is not stable.*

Proof. Consider a hypersurface Σ near $r = 0$ and let ω be ω_X restricted to Σ. By Lemma 4.1, $[\omega] \neq 0$, but $[\omega^2] = 0$. Since SM fibres over M with fibres given by 2-spheres transveral to the weak bundles the same holds true for Σ (recall that under perturbations the stable and unstable bundles vary continuously). Finally we note that (Σ, ω) is 1/2-pinched. Indeed, recall that for the geodesic flow of M, we have

$$|d\phi_t(\xi)| = e^{-t}|\xi| \text{ for } \xi \in E^s,$$

$$|d\phi_t(\xi)| = e^{t}|\xi| \text{ for } \xi \in E^u.$$

Thus for a flow φ_t which is C^1 close to ϕ_t we get

$$\frac{1}{C}|\xi|e^{-At} \leq |d\varphi_t(\xi)| \leq C|\xi|e^{-at} \text{ for } \xi \in E^s \text{ and } t \geq 0,$$

$$\frac{1}{C}|\xi|e^{-At} \leq |d\varphi_{-t}(\xi)| \leq C|\xi|e^{-at} \text{ for } \xi \in E^u \text{ and } t \geq 0,$$

where all the constants C, A, a are close to 1. Thus (Σ, ω) is 1/2-pinched.

We can now apply Theorem 3.1 to conclude that if Σ near $r = 0$ is stable, then the weak bundles must be C^∞. However, a theorem of Hasselblatt [9, Corollary 1.10] asserts that an open and dense set of symplectic Anosov systems does not have weak bundles of class $C^{2-\varepsilon}$. Thus a typical hypersurface Σ near $r = 0$ cannot be stable. $\square$

Remark 4.3. It is possible to prove the last theorem without appealing to Theorem 2.2. An inspection of the proof of Theorem 3.1 shows that since $d\phi_t$ preserves $\mathbb{J}$, all the closed orbits are actually 2-bunched in the terminology of [9], and the perturbation result in [9] implies that an open and dense set of symplectic Anosov systems does not have all closed orbits being 2-bunched. Of course, the conclusion of Theorem 3.1 is stronger if we use Theorem 2.2.

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