

THE TRUNKENNESS OF A VOLUME-PRESERVING VECTOR FIELD

ANA RECHTMAN, PIERRE DEHORNOY

ABSTRACT. We construct a new invariant—the *trunkness*—for volume-preserving vector fields on \mathbb{S}^3 up to volume-preserving homeomorphism. We prove that the trunkness is independent from the helicity and that it is the limit of a knot invariant (called the trunk) computed on long pieces of orbits.

CONTENTS

1. Trunk of knots	4
2. Trunkness of measure preserving vector fields	5
3. Independence of helicity	9
4. Trunkness and the existence of periodic orbits	10
5. Trunkness of knotted tubes	16
References	17

The problem we address here is the construction of new invariants of volume-preserving vector fields on \mathbb{S}^3 , or on compact domains of \mathbb{R}^3 , up to volume-preserving diffeomorphisms. This problem is motivated by at least two physical situations. First if v is the velocity field of a time-dependant ideal fluid satisfying the Euler equations (ideal hydrodynamics) then its vorticity field $\text{curl } v$ is transported by the flow of v [Hel1858]. Second if B is the magnetic field in an incompressible plasma (ideal magnetodynamics), then B turns out to be transported by the velocity field as long as the latter does not develop singularities [Wol58]. In these contexts, invariants of $\text{curl } v$ or B up to volume-preserving diffeomorphisms yield time-independent invariants of the system.

Not so many such invariants exist. The first one was discovered by William Thomson [Tho1867]: if the considered field has a periodic orbit or a periodic tube, then its knot type is an invariant (this remark led to the development of knot theory by Peter G. Tait [Tai1877]). However it may not be easy to find periodic orbits, and even then such an invariant only takes a small part of the field into account.

The main known invariant is called *helicity*. It is defined by the formula $\text{Hel}(v) = \int v \cdot u$, where $u = \text{curl}^{-1}(v)$ is an arbitrary vector-potential of v . It was discovered by Woltjer, Moreau, and Moffatt [Wol58, Mor61, Mof69]. Helicity is easy to compute or to approximate since it is enough to exhibit a vector-potential of the considered vector field, to take the scalar product and to integrate. The connection with knot theory was sketched by Moffatt [Mof69] and deepened by Arnold [Arn73] as follows. Denote by $k_X(p, t)$ a loop starting at the point p , tangent to the vector field X for a time t and closed by an arbitrary segment of bounded length. Denote by Lk the linking number of loops. Arnold showed that for almost every p_1, p_2 , the limit $\lim_{t_1, t_2 \rightarrow \infty} \frac{1}{t_1 t_2} \text{Lk}(k_X(p_1, t_1), k_X(p_2, t_2))$ exists (see also [Vog02] for a corrected statement). Moreover if X is ergodic the limit coincides almost everywhere with $\text{Hel}(X)$ (for a non-ergodic vector field, one has to average the previous limit to obtain the helicity).

The idea of considering knot invariants of long pieces of orbits of the vector field was pursued by Gambaudo and Ghys [GG01] who considered ω -signatures of knots, Baader [Baa11] who considered

linear saddle invariants, and Baader and Marché [BM12] who considered Vassiliev's finite type invariants. In every case, it is shown that $\lim_{t \rightarrow \infty} \frac{1}{t^n} V(k_X(p, t))$ exists, where V is the considered invariant and n a suitable exponent called the *order* of the asymptotic invariant. However all these constructions have the drawback that they do not yield any new invariant for ergodic vector fields, as in this case the obtained limits are all functions of the helicity.

Recently, it was proved by Kudryavtseva for vector fields obtained by suspending an area-preserving diffeomorphism of a surface [Kud14] and for non-vanishing vector fields [Kud16], and then by Enciso, Peralta-Salas and Torres de Lizaaur [EPT16] for arbitrary volume-preserving vector fields, that every invariant that is *regular integral* (in the sense that its Fréchet derivative is the integral of a continuous kernel) is a function of helicity, see the cited articles for precise statements. These results give a satisfactory explanation of why most constructions yield invariants that are functions of helicity for ergodic vector fields. However they do not rule out the existence of other invariants, but imply that such invariants cannot be *too* regular.

An example of such another invariant is the asymptotic crossing number considered by Freedman and He [FH91]. The advantage is that it is not proportional to helicity, but the disadvantage is that it is hard to compute, even on simple examples.

In this article we consider a less known knot invariant called the trunk (see Definition 1.1 below). It was defined by Ozawa [Ozw10], building on the concept of *thin position* that was introduced by Gabai [Gab87] for solving the R-conjecture. Less famous than the invariants previously studied in the context of vector fields, the trunk has the advantage that its definition relies on surfaces transverse to the considered knot, so that it is easy to transcribe in the context of vector fields. The invariant depends on an invariant measure for the flow of the vector field that may or may not be a volume, and is invariant under homeomorphisms that preserve this measure. Given a μ -preserving vector field X and a surface S , the *geometric flux* through S is the infinitesimal volume that crosses S in both directions (see Definition 2.1), it is denoted by $\text{Flux}(X, \mu, S)$. Our invariant is a minimax of the geometric flux, where one minimizes over all height functions and maximizes over the levels of the considered height function.

Definition 1. *Assume that X is a vector field on \mathbb{S}^3 or on a compact domain of \mathbb{R}^3 that preserves a probability measure μ . Denote by ϕ_X the flow of X . The trunkness of X with respect to μ is*

$$\text{Tks}(X, \mu) := \inf_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in [0,1]} \text{Flux}(X, \mu, h^{-1}(t)) = \inf_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in [0,1]} \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi_X^{[0,\epsilon]}(h^{-1}(t))).$$

By a height function on \mathbb{S}^3 we refer to a function with only two singular points and whose level sets are 2-dimensional spheres. On \mathbb{R}^3 , the level sets of a height function are all topological planes.

From the definition, it is straightforward that the trunkness of a vector field is invariant under diffeomorphisms that preserve the measure μ . More is true, the trunkness is invariant under homeomorphisms that preserve μ .

Theorem A. *Assume that X_1 and X_2 are vector fields on \mathbb{S}^3 or on a compact domain of \mathbb{R}^3 that preserve a probability measure μ and that there is a μ -preserving homeomorphism f that conjugates the flows of X_1 and X_2 . Then we have*

$$\text{Tks}(X_1, \mu) = \text{Tks}(X_2, \mu).$$

What we do in this paper is to prove several properties of this new invariant. The first one is a continuity result. It is more easily stated in terms of currents, but we also provide corollaries that do not rely on this vocabulary. Given a vector field X and a measure μ , we can define a normal 1-current $C_{(X,\mu)}$: for α any differential 1-form $C_{(X,\mu)}(\alpha) = \int \alpha(X) d\mu$, where the integral is taken on the ambient space. We consider the space of normal currents endowed with the mass topology (see [Mor00]).

Theorem B. *The trunkness is a continuous functional on the space of normal currents.*

Corollary C. *Suppose that $(X_n, \mu_n)_{n \in \mathbb{N}}$ is a sequence of measure-preserving vector fields such that $(X_n)_{n \in \mathbb{N}}$ converges to X in the C^0 -topology and $(\mu_n)_{n \in \mathbb{N}}$ converges to μ in the weak-* sense. Then we have*

$$\lim_{n \rightarrow \infty} \text{Tks}(X_n, \mu_n) = \text{Tks}(X, \mu).$$

For K a knot, we denote by $\text{Tk}(K)$ its trunk (see Definition 1.1 below). Now for p a point in the ambient manifold and $t > 0$, denote by $k_X(p, t)$ the closed curve obtained by concatenating the orbit segment between p and $\phi_X^t(p)$ and a short path between these two points. As for the asymptotic linking number, there is a system of short paths such that we obtain a simple closed curve for μ -almost all points and almost all times [Vog02]. The next corollary states that trunkness is an asymptotic invariant in the sense of Arnold [AK98], and its order is 1.

Corollary D. *Assume that X is a μ -preserving vector field and that X is ergodic with respect to μ , then, for μ -almost every p , the limit*

$$\lim_{t \rightarrow \infty} \frac{1}{t} \text{Tk}(k_X(p, t))$$

exists and is equal to $\text{Tks}(X, \mu)$.

The above continuity results allow us to compute the trunkness of some explicit vector fields on \mathbb{S}^3 called Seifert flows. These computations in turn show that the trunkness is not dictated by helicity, even in the case of ergodic vector fields, thus contrasting with most previously known knot-theoretical constructions.

Theorem E. *There is no function f such that for every ergodic volume-preserving vector field X on \mathbb{S}^3 one has $\text{Tks}(X, \mu) = f(\text{Hel}(X, \mu))$.*

Finally we address the question of what happens if for a non-singular vector field on \mathbb{S}^3 there is a function that achieves the trunkness, or in other words if the infimum in Definition 1 is a minimum.

Theorem F. *Let X be a non-singular vector field on \mathbb{S}^3 preserving the measure μ and h a height function such that*

$$\text{Tks}(X, \mu) = \max_{t \in [0, 1]} \text{Flux}(X, \mu, h^{-1}(t))$$

Then X has an unknotted periodic orbit.

One of the main motivations for constructing topological invariants of a vector field X is to find lower bound on the energies $E_p(X) := \int |X|^p d\mu$. Indeed since a topological invariant yields a time-independent invariant of the physical system, an energy bound in term of a topological invariant will also be time-independent, although the energy may vary when the vector field is transported under (volume-preserving) diffeomorphisms. Such energy bounds exist for the helicity and for the asymptotic crossing number. We do not know whether the trunkness bounds the energy.

The plan of the article is as follows. First we recall in Section 1 the definition of the trunk of a knot in order to make the definition for vector fields natural. Then we define the trunkness of a measure-preserving vector field and prove Theorems A and B in Section 2. Using Theorem B we compute of trunkness of Seifert vector fields and prove Theorem E in Section 3. We prove Theorem F in Section 4, where we discuss why the converse implication does not holds. Finally in Section 5 we compute the trunkness of some vector fields supported in the tubular neighborhood of a link.

Acknowledgements. We thank Michel Boileau who suggested to study the trunk instead of the genus for vector fields during a visit of P.D. to Toulouse in 2013. We also thank the referee for his comments and suggestions.

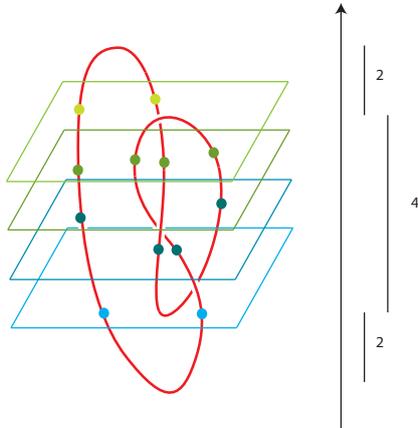


FIGURE 1. The trunk of the trefoil knot: the maximal number of intersection points between a horizontal level and the proposed embedding is 4. This number cannot be reduced under isotopy, hence the trunk of the trefoil is 4.

1. TRUNK OF KNOTS

For K a knot, we denote by \mathcal{K} the set of all embeddings of K into \mathbb{R}^3 . The *standard height function* on \mathbb{R}^3 is the function $h_z : \mathbb{R}^3 \rightarrow \mathbb{R}, (x, y, z) \mapsto z$. Every level $h_z^{-1}(t)$ is a 2-dimensional plane. An embedding $k \in \mathcal{K}$ is said to be in *Morse position* with respect to h_z if the restriction of h_z to k is a Morse function. In this case there are only finitely many points at which k is tangent to a level of h_z .

Definition 1.1. Assume that k is an embedded knot in \mathbb{R}^3 that is in Morse position with respect to h_z . The *trunk of the curve k relatively to h_z* is

$$\text{tk}_{h_z}(k) := \max_{t \in \mathbb{R}} \#\{k \cap h_z^{-1}(t)\}.$$

The *trunk of a knot K* is then defined by

$$\text{Tk}(K) := \min_{k \in \mathcal{K}} \text{tk}_{h_z}(k) = \min_{k \in \mathcal{K}} \max_{t \in \mathbb{R}} \#\{k \cap h_z^{-1}(t)\}.$$

The trunk of a knot was defined by M. Ozawa [Ozw10] and motivated by D. Gabai's definition of the waist of a knot [Gab87].

Example 1.2. A knot is trivial if and only if its trunk equals 2. Indeed the embedding as the boundary of a vertical disc shows that the trunk is less than or equal to 2, and every embedding in Morse position of the trivial knot has to intersect some horizontal plane in at least two points. Conversely, if the trunk of a knot is equal to 2, then it admits an embedding that intersects every horizontal plane in at most two points. The union of the segments that connect these pairs of points is a disc bounded by the knot, implying that the knot is trivial.

Example 1.3. For p, q in \mathbb{N} , the torus knot $T(p, q)$ can be realized as the closure of a braid with q strands, yielding $\text{Tk}(T(p, q)) \leq 2q$. By symmetry one also gets $\text{Tk}(T(p, q)) \leq 2p$. Actually, one can prove $\text{Tk}(T(p, q)) = 2 \min(p, q)$, see Remark 1.2 in [Ozw10].

Instead of fixing the function and changing the knot up to isotopy, one can fix the knot and change the function up to orientation preserving diffeomorphism. With this in mind, one defines a *height function* on \mathbb{R}^3 as a function obtained by precomposing h_z by a diffeomorphism, that is, a function of the form

$$\begin{aligned} h : \mathbb{R}^3 &\rightarrow \mathbb{R} \\ (x, y, z) &\mapsto h_z(\phi(x, y, z)) \end{aligned}$$

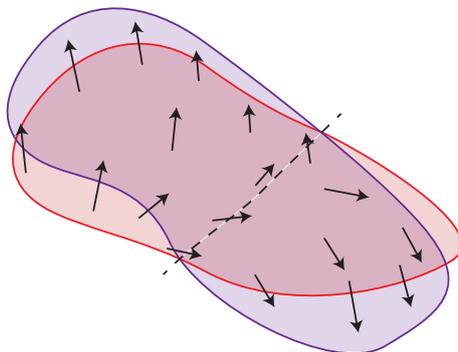


FIGURE 2. For S a piece of a surface (in red), the domain $\phi^{[0, \epsilon]}(S)$ is roughly the part of the space located between S and $\phi^\epsilon(S)$. It is pinched around those points where the vector field is tangent to S . Its volume is $\epsilon \cdot \text{Flux}(X, \mu, S)$ at the first order.

for ϕ an orientation preserving diffeomorphism of \mathbb{R}^3 . In particular, a height function is a function whose levels are smooth planes. For K a knot and k a fixed embedding of K in \mathbb{R}^3 , one can then define

$$\text{tk}_h(k) := \max_{t \in \mathbb{R}} \#\{k \cap h^{-1}(t)\},$$

so that we have the alternative definition

$$(1) \quad \text{Tk}(K) = \min_{\substack{h \text{ height} \\ \text{function}}} \text{tk}_h(k) = \min_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in \mathbb{R}} \#\{k \cap h^{-1}(t)\}.$$

2. TRUNKENNESS OF MEASURE PRESERVING VECTOR FIELDS

We use the definition of Equation (1) to define the trunkeness of a vector field with respect to an invariant measure. The main question then concerns the analog of the number of intersection points of a surface with a curve when the curve is replaced by a vector field. A natural answer is the *geometric flux*. If X is a vector field that preserves a measure μ given by a volume element Ω , one can then consider the 2-form $\iota_X \Omega$. For S a piece of oriented surface that is positively transverse to X , the integral $\int_S \iota_X \Omega$ computes the instantaneous volume that crosses S . In other words, by Fubini Theorem we have $\mu(\phi^{[0, t]}(S)) = (\int_S \iota_X \Omega) \cdot t$. On the other hand if S is negatively transverse to X we have $\mu(\phi^{[0, t]}(S)) = -(\int_S \iota_X \Omega) \cdot t$. Therefore in this case, for any surface S , the instantaneous volume crossing S is given by $\int_S |\iota_X \Omega|$. Now if the measure μ is not given by integrating a volume form one cannot consider the above integral, but the quantity $\mu(\phi^{[0, t]}(S))$ still makes sense for any piece of surface S (see Figure 2).

Definition 2.1. For X a vector field that preserves a measure μ and for S a surface, the *geometric flux* of (X, μ) through S is

$$\text{Flux}(X, \mu, S) := \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi^{[0, \epsilon]}(S)).$$

This definition generalizes the number of intersection points of a knot with a surface. Indeed one can see an embedding k of a knot K as a vector field with a particular invariant measure in the following way: consider a non-singular vector field X_k that is tangent to k at every point and denote by ϕ_k^t the induced flow. Since k is closed, ϕ_k is T_k -periodic for some $T_k > 0$. The Dirac linear measure associated to X_k is defined by

$$\mu_k(A) = \text{Leb}(\{t \in [0, T_k], \phi_k^t(x) \in A\})$$

where A is a measurable set and x an arbitrary point on k . The measure μ_k is X_k -invariant and has total mass T_k . In this setting, for S a surface that intersects k in finitely many points, a point p in the set $k \cap S$ has μ_k -measure zero and thus cannot be detected by the measure. But by definition of μ_k the set $\phi_k^{[0, \epsilon]}(p)$ is an arc of k of μ_k -measure ϵ and since $k \cap S$ is made of finitely

many points, for ϵ small enough, the set $\phi_k^{[0,\epsilon]}(k \cap S)$ has μ_k -measure exactly $\epsilon \cdot \#\{k \cap S\}$. In other words, one has

$$\#\{k \cap S\} = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu_k(\phi_k^{[0,\epsilon]}(k \cap S)).$$

As μ_k is concentrated on k , we thus have

$$(2) \quad \#\{k \cap S\} = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu_k(\phi_k^{[0,\epsilon]}(S)) = \text{Flux}(X_k, \mu_k, S),$$

so the geometric flux indeed generalizes the number of intersection points.

We now mimic for vector fields the definition of the trunk of a knot. In order to have a well-defined maximum, in what follows we assume the vector fields are on a compact domain $D^3 \subset \mathbb{R}^3$ or on the 3-sphere $\mathbb{S}^3 = \mathbb{R}^3 \cup \infty$. In the later case, we define the *standard height function*

$$\begin{aligned} h_0 : \mathbb{S}^3 &\rightarrow [0, 1] \\ (x, y, z) &\mapsto 1 - \frac{1}{1 + x^2 + y^2 + z^2}. \end{aligned}$$

The levels $h_0^{-1}(0)$ and $h_0^{-1}(1)$ consist of the points $(0, 0, 0)$ and ∞ respectively and every other level $h_0^{-1}(t)$ is a 2-dimensional sphere of radius $\sqrt{t/(1-t)}$ centered at the origin. A *height function* on \mathbb{S}^3 is then a function obtained by precomposing by an orientation preserving diffeomorphism ϕ of \mathbb{S}^3 , that is, a function of the form $h : \mathbb{S}^3 \rightarrow [0, 1]$, $(x, y, z) \mapsto h_0(\phi(x, y, z))$.

Definition 2.2. Let X be a vector field whose flow preserves a measure μ on a compact domain of \mathbb{R}^3 or on \mathbb{S}^3 , and h a height function. We set

$$\text{tks}_h(X, \mu) := \max_{t \in [0,1]} \text{Flux}(X, \mu, h^{-1}(t)) = \max_{t \in [0,1]} \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi^{[0,\epsilon]}(h^{-1}(t))).$$

The *trunkness* of (X, μ) is defined as

$$\begin{aligned} \text{Tks}(X, \mu) &:= \inf_{\substack{h \text{ height} \\ \text{function}}} \text{tks}_h(X, \mu) = \inf_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in [0,1]} \text{Flux}(X, \mu, h^{-1}(t)) \\ &= \inf_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in [0,1]} \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi^{[0,\epsilon]}(h^{-1}(t))). \end{aligned}$$

Note that we can only consider an infimum instead of a minimum as in the case of knots. In Section 4 we prove that for non-singular vector fields, if the trunkness is a minimum then the vector field possesses an unknotted periodic orbit.

If the invariant measure μ is given by the integration of a volume form Ω , we get the alternative definitions

$$\text{tks}_h(X, \Omega) = \max_{t \in [0,1]} \int_{h^{-1}(t)} |\iota_X \Omega|, \quad \text{and} \quad \text{Tks}(X, \Omega) = \inf_{\substack{h \text{ height} \\ \text{function}}} \max_{t \in [0,1]} \int_{h^{-1}(t)} |\iota_X \Omega|.$$

We now prove the invariance under homeomorphism.

Proof of Theorem A. Assume without loss of generality that there is a homeomorphism f preserving the measure μ such that $f \cdot \phi_{X_1}^t = \phi_{X_2}^t \cdot f$, with $\phi_{X_i}^t$ the flow of X_i , and assume by contradiction that $\text{Tks}(X_1, \mu) < \text{Tks}(X_2, \mu)$. Let $0 < \delta = \text{Tks}(X_2, \mu) - \text{Tks}(X_1, \mu)$. Take h_n to be a sequence of (differentiable) height functions such that

$$\lim_{n \rightarrow \infty} \text{tks}_{h_n}(X_1, \mu) = \text{Tks}(X_1, \mu).$$

By construction, there is a sequence $\{\phi_n\}$ of orientation preserving diffeomorphisms such that $h_n = h_0 \cdot \phi_n$, for h_0 the standard height function on \mathbb{R}^3 or \mathbb{S}^3 . For each n , let Φ_n be a diffeomorphism that is C^0 -close to the homeomorphism $\phi_n \cdot f^{-1}$, then $H_n = h_0 \cdot \Phi_n$ is a height function that is

C^0 -close to $\tilde{h}_n = h_n \cdot f^{-1} = h_0 \cdot (\phi_n \cdot f^{-1})$. Thus for every $t \in [0, 1]$ and for ϵ small enough, we have

$$\left| \frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(H_n^{-1}(t))) - \frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(\tilde{h}_n^{-1}(t))) \right| < \frac{\delta}{4}.$$

Fix n large enough so that $\text{tks}_{h_n}(X_1, \mu) - \text{Tks}(X_1, \mu) < \frac{\delta}{4}$ and now set T in $[0, 1]$ so that

$$\text{tks}_{H_n}(X_2, \mu) = \text{Flux}(X_2, \mu, H_n^{-1}(T)).$$

We have two possibilities:

- (1) If $\text{Flux}(X_2, \mu, H_n^{-1}(T)) \geq \text{Flux}(X_2, \mu, \tilde{h}_n^{-1}(T))$, then for ϵ small enough

$$\frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(H_n^{-1}(T))) \leq \frac{\delta}{4} + \frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(\tilde{h}_n^{-1}(T))).$$

Hence

$$\begin{aligned} \text{Tks}(X_2, \mu) &\leq \text{tks}_{H_n}(X_2, \mu) = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(H_n^{-1}(T))) \\ &\leq \frac{\delta}{4} + \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi_{X_2}^{[0, \epsilon]}(\tilde{h}_n^{-1}(T))) \\ &= \frac{\delta}{4} + \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi_{X_1}^{[0, \epsilon]}(h_n^{-1}(T))) \\ &\leq \frac{\delta}{4} + \text{tks}_{h_n}(X_1, \mu) < \frac{\delta}{2} + \text{Tks}(X_1, \mu). \end{aligned}$$

Thus, $\delta = \text{Tks}(X_2, \mu) - \text{Tks}(X_1, \mu) < \frac{\delta}{2}$, a contradiction proving Theorem A in this case.

- (2) If $\text{Flux}(X_2, \mu, H_n^{-1}(T)) < \text{Flux}(X_2, \mu, \tilde{h}_n^{-1}(T))$, then

$$\begin{aligned} \text{tks}_{H_n}(X_2, \mu) &= \text{Flux}(X_2, \mu, H_n^{-1}(T)) \\ &< \text{Flux}(X_2, \mu, \tilde{h}_n^{-1}(T)) = \text{Flux}(X_1, \mu, h_n^{-1}(T)) \\ &\leq \text{tks}_{h_n}(X_1, \mu) < \text{Tks}(X_1, \mu) + \frac{\delta}{4} < \text{Tks}(X_2, \mu). \end{aligned}$$

Thus, $\text{tks}_{H_n}(X_2, \mu) < \text{Tks}(X_2, \mu)$, a contradiction to the definition of the trunkeness.

This finishes the proof of Theorem A. \square

Computing the trunkeness of a vector field is not easy in general. Considering a given height function gives an upper bound on the trunkeness, but lower bounds are harder to find. Theorem B and its corollaries provide useful tools.

Proof of Theorem B. Set M to be the ambient manifold, that is either \mathbb{S}^3 or a compact domain in \mathbb{R}^3 . Recall that to define the mass of a current, we need a Riemannian metric on the ambient manifold. So we fix one Riemannian metric on M .

By definition of the current associated to (X, μ) , for every differential 1-form α we have

$$C_{(X, \mu)}(\alpha) = \int \alpha(X) d\mu = \int \alpha(Y) d\nu,$$

where $Y = \frac{X}{\|X\|}$ is a unit vector field and $\nu = \|X\| \mu$. Observe that we can normalize X whenever $X \neq 0$, but we are just interested in the region of the ambient manifold that is in the support of X and in the support of μ . Then the mass of $C_{(X, \mu)}$ is given by

$$\mathbf{M}(C_{(X, \mu)}) = \sup_{\alpha, \|\alpha\| \leq 1} \left(\int \alpha(X) d\mu \right) = \nu(M).$$

Let (X_n, μ_n) be a sequence of vector fields with invariant measures and (X, μ) be vector field preserving μ such that

$$\mathbf{M}(C_{(X, \mu)} - C_{(X_n, \mu_n)}) = \delta_n \xrightarrow{n \rightarrow \infty} 0.$$

Then for every measurable set $A \subset M$ we have that $|\nu(A) - \nu_n(A)| < \delta_n$. Assuming that $C_{(X_n, \mu_n)}$ converges to $C_{(X, \mu)}$ with respect to the mass implies that ν_n converges in weak- \star topology to ν .

Our goal is to prove that $|\text{Tks}(X, \mu) - \text{Tks}(X_n, \mu_n)|$ tends to zero. Fix $\epsilon > 0$ and small, and let $N > 0$ be such that for every $n \geq N$ we have that $\delta_n < \epsilon^2$.

We first prove the inequality $\text{Tks}(X, \mu) \leq \text{Tks}(X_n, \mu_n) + 3\epsilon$ for $n \geq N$. The argument consists in showing that height functions that approximate $\text{Tks}(X_n, \mu_n)$ give upper bounds for $\text{Tks}(X, \mu)$. For each $n > N$, let h_n be a height function such that $|\text{tks}_{h_n}(X_n, \mu_n) - \text{Tks}(X_n, \mu_n)| < \epsilon$, and let $t_n \in [0, 1]$ be such that $\max_{t \in [0, 1]} \text{Flux}(X, \mu, h_n^{-1}(t)) = \text{Flux}(X, \mu, h_n^{-1}(t_n))$. We have

$$\begin{aligned} \text{Tks}(X, \mu) - \text{Tks}(X_n, \mu_n) &= (\text{Tks}(X, \mu) - \text{tks}_{h_n}(X, \mu)) + (\text{tks}_{h_n}(X, \mu) - \text{tks}_{h_n}(X_n, \mu_n)) \\ &\quad + (\text{tks}_{h_n}(X_n, \mu_n) - \text{Tks}(X_n, \mu_n)) \\ &\leq 0 + \left(\max_{t \in [0, 1]} \text{Flux}(X, \mu, h_n^{-1}(t)) - \max_{t \in [0, 1]} \text{Flux}(X_n, \mu_n, h_n^{-1}(t)) \right) + \epsilon \\ &\leq (\text{Flux}(X, \mu, h_n^{-1}(t_n)) - \text{Flux}(X_n, \mu_n, h_n^{-1}(t_n))) + \epsilon \\ &= \lim_{\epsilon' \rightarrow 0} \frac{1}{\epsilon'} \left(\nu(\phi_Y^{[0, \epsilon']}(h_n^{-1}(t_n))) - \nu_n(\phi_{Y_n}^{[0, \epsilon']}(h_n^{-1}(t_n))) \right) + \epsilon \\ &\leq \frac{1}{\epsilon} \left(\nu(\phi_Y^{[0, \epsilon]}(h_n^{-1}(t_n))) - \nu_n(\phi_{Y_n}^{[0, \epsilon]}(h_n^{-1}(t_n))) \right) + 2\epsilon \\ &\leq \frac{\delta_n}{\epsilon} + 2\epsilon \\ &< 3\epsilon. \end{aligned}$$

For the converse inequality $\text{Tks}(X_n, \mu_n) \leq \text{Tks}(X, \mu) + 3\epsilon$ for $n \geq N$, the argument is similar, except that we only have to consider one height function h such that $|\text{tks}_h(X, \mu) - \text{Tks}(X, \mu)| < \epsilon$, and set $t_n \in [0, 1]$ such that $\max_{s \in [0, 1]} \text{Flux}(X_n, \mu_n, h^{-1}(s)) = \text{Flux}(X_n, \mu_n, h^{-1}(t_n))$. A similar computation gives

$$\begin{aligned} \text{Tks}(X_n, \mu_n) - \text{Tks}(X, \mu) &= (\text{Tks}(X_n, \mu_n) - \text{tks}_h(X_n, \mu_n)) \\ &\quad + (\text{tks}_h(X_n, \mu_n) - \text{tks}_h(X, \mu)) + (\text{tks}_h(X, \mu) - \text{Tks}(X, \mu)) < 3\epsilon. \end{aligned}$$

□

Proof of Corollary C. If X_n tends to X in the C^0 -topology and μ_n tends to μ in the weak-* sense, then the currents $C_{(X_n, \mu_n)}$ tend to $C_{(X, \mu)}$ in the mass topology, so Theorem B directly implies that $\text{Tks}(X_n, \mu_n)$ tends to $\text{Tks}(X, \mu)$. □

Corollary D relates the trunkeness of an ergodic vector field to the trunk of its (almost-)periodic orbits.

Proof of Corollary D. For any vector field X , the discussion after Definition 2.1 shows how to associate natural Dirac linear measures to its flow as follows: for $t > 0$ and p a point, $\mu_{p,t}$ is defined by $\mu_{p,t}(A) := \text{Leb}(\{s \in [0, t], \phi_X^s(p) \in A\})$. Its total mass is t . That is why we rather consider the normalized measure $\frac{1}{t}\mu_{p,t}$. If p is on a t -periodic orbit, then $\mu_{p,t}$ is X -invariant. Now if X is ergodic with respect to μ then, for almost every p and for every sequence $t_n \rightarrow \infty$, the normalized linear Dirac masses $\frac{1}{t_n}\mu_{p,t_n}$ tend to μ in the weak-* sense.

Recall that $k_X(p, t_n)$ is the knot obtained by following the orbit of p for a time t_n concatenated with a short path from $\phi_X^{t_n}(p)$ to p , as explained in the introduction. We additionally require that the short arc is tangent to X at p and at $\phi_X^{t_n}(p)$, this can be realized by an isotopy of $k_X(p, t_n)$. Denote by K_n the knot $k_X(p, t_n)$, by X_n a vector field, defined on K_n only, that is equal to X on the part of K_n that correspond to an arc of orbit of X , tangent to the short path on the short path, and by μ'_n the normalized Dirac linear measure associated to X_n . Then the currents $C_{(X_n, \mu'_n)}$ tend to $C_{(X, \mu)}$ in the mass topology, and so Theorem B implies that $\text{Tks}(X_n, \mu'_n)$ tends to $\text{Tks}(X, \mu)$.

From Equation (2), for every n and for every height function h , unless the knot K_n can be made tangent to $h^{-1}(t)$, we get

$$\#\{K_n \cap h^{-1}(t)\} = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu'_n(\phi_{X_n}^{[0, \epsilon]}(h^{-1}(t))),$$

so that $\text{Tks}(X_n, \mu'_n)$ is equal to $\frac{1}{t}\text{Tk}(k_X(p, t))$. The exceptional case where K_n can be made tangent to $h^{-1}(t)$ means that K_n is trivial. So either for almost all p and t_n the knots K_n are trivial, in which case we have $\text{Tks}(X, \mu) = 0$, or the convergence implies that $\lim_{t \rightarrow \infty} \frac{1}{t}\text{Tk}(k_X(p, t))$ exists and is equal to $\text{Tks}(X, \mu)$. \square

3. INDEPENDENCE OF HELICITY

As mentioned in the introduction, the helicity is a well-known invariant of vector fields up to volume-preserving diffeomorphism. In this section, all vector fields are on the sphere \mathbb{S}^3 and preserve a volume form, that we denote by Ω . For X such a vector field, Cartan's formula implies that $\iota_X \Omega$ is a closed 2-form, and since the ambient manifold is simply connected it is exact. We may then write $\iota_X \Omega = d\alpha$, for α some differential 1-form. The helicity of X is defined as

$$\text{Hel}(X) := \int_{\mathbb{S}^3} \alpha \wedge d\alpha.$$

It does not depend on the choice of the primitive α [AK98].

As we recalled in the introduction most known asymptotic invariants are in fact proportional to a power of helicity [Arn73, GG01, Baa11, BM12]. The goal of this section is to prove that the trunkeness of a vector field is not a function of its helicity. In order to do so we compute the trunkeness and the helicity of a vector field that preserves the invariant tori of a Hopf fibration of \mathbb{S}^3 .

Considering \mathbb{S}^3 as the unit sphere $\{(z_1, z_2) \in \mathbb{C}^2, |z_1|^2 + |z_2|^2 = 1\}$, the *Seifert flow of slope* (α, β) is the flow $\phi_{\alpha, \beta}$ given by

$$\phi_{\alpha, \beta}^t(z_1, z_2) := (z_1 e^{i2\pi\alpha t}, z_2 e^{i2\pi\beta t}).$$

It is generated by the vector field $X_{\alpha, \beta}$ given by $X_{\alpha, \beta}(z_1, z_2) = (i2\pi\alpha z_1, i2\pi\beta z_2)$. This flow preserves the standard volume form, that is, the volume form Ω_{Haar} associated to the Haar measure of \mathbb{S}^3 . The flow has two distinctive periodic orbits corresponding to $z_1 = 0$ and $z_2 = 0$ that are trivial knots in \mathbb{S}^3 . The tori $|z_1/z_2| = r$ for $0 < r < \infty$ are invariant and the flow on each one of them is the linear flow of slope α/β . If α/β is rational, put $\alpha/\beta = p/q$ with $p, q \in \mathbb{N}$ coprime. Then every orbit of $\phi_{\alpha, \beta}$, different from the two trivial ones, is a torus knot of type $T(p, q)$.

The helicity of $\phi_{\alpha, \beta}$ is equal to $\alpha\beta$. To compute it in the rational case $(\alpha, \beta) = (p, q)$ with p, q coprime, observe that all the orbits except two are periodic of period 1. The linking number of an arbitrary pair of such orbits is pq . Therefore the asymptotic linking number (also called asymptotic Hopf invariant) equals pq and, by Arnold's Theorem [Arn73], so does the helicity. For the general case of (α, β) not necessarily rational, it is enough to use the continuity of the helicity, since $X_{\alpha, \beta}$ can be approximated by a sequence of Seifert flows with rational slope.

Proposition 3.1. *The trunkeness of the Seifert flow $\phi_{\alpha, \beta}$ with respect to the standard volume form Ω_{Haar} is equal to $2 \min(\alpha, \beta)$.*

Proof. Let us first prove $\text{Tks}(X_{\alpha, \beta}, \Omega_{\text{Haar}}) \leq 2\beta$. For this it is enough to exhibit a height function h that yields $\text{tks}_h(X_{\alpha, \beta}, \Omega_{\text{Haar}}) = 2\beta$. First define $\infty = (0, 1)$ and $0 = (0, -1)$ in $\mathbb{S}^3 \subset \mathbb{C}^2$ and take the stereographic projection to identify

$$\{(z_1, z_2) \in \mathbb{C}^2, |z_1|^2 + |z_2|^2 = 1\} \simeq \mathbb{R}^3 \cup \{\infty\}.$$

Take now as h the standard height function h_0 of $\mathbb{R}^3 \cup \{\infty\}$. The spheres are centered at $0 \in \mathbb{R}^3$ that corresponds to the point $(0, -1) \in \mathbb{S}^3 \subset \mathbb{C}^2$, hence the orbit $z_1 = 0$ intersects twice each level sphere $h_0^{-1}(t)$. The middle sphere, $S = h_0^{-1}(1/2)$, contains the other special orbit $z_2 = 0$ and is the only sphere that intersects all the orbits of $\phi_{\alpha, \beta}$. Then the function $t \mapsto \int_{h_0^{-1}(t)} |\iota_{X_{\alpha, \beta}} \Omega_{\text{Haar}}|$ has a maximum for $t = 1/2$.

For computing $\int_S |\iota_{X_{\alpha, \beta}} \Omega_{\text{Haar}}|$, we remark that the 2-sphere S has the orbit $(e^{i2\pi\alpha t}, 0)$ as an equator, that the flow is positively transverse to the northern hemisphere and negatively transverse to the southern hemisphere. Then the integral $\int_S |\iota_{X_{\alpha, \beta}} \Omega_{\text{Haar}}|$ is equal to twice the flux of $X_{\alpha, \beta}$ through any disc bounded by the curve $(e^{i2\pi\alpha t}, 0)$. Consider the flat disc D in \mathbb{S}^3

bounded by $(e^{i2\pi\alpha t}, 0)$. The first return time to D is constant and equal to $1/\beta$, so the flux multiplied by $1/\beta$ gives the total volume of \mathbb{S}^3 , that is 1. Therefore $\text{Flux}(X_{\alpha,\beta}, \Omega_{\text{Haar}}, D)$ is equal to β , and we obtain $\text{tks}_{h_0}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = \int_S |\iota_{X_{\alpha,\beta}} \Omega_{\text{Haar}}| = 2\beta$. By symmetry, we then have $\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) \leq 2 \min(\alpha, \beta)$.

For proving the converse inequality $\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) \geq 2 \min(\alpha, \beta)$, we approximate $X_{\alpha,\beta}$ (in the C^∞ -topology) by a sequence $(X_{p_n/r_n, q_n/r_n})_{n \in \mathbb{N}}$, where p_n, q_n, r_n are integer numbers. Theorem C yields

$$\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = \lim_{n \rightarrow \infty} \text{Tks}(X_{p_n/r_n, q_n/r_n}, \Omega_{\text{Haar}}).$$

As the trunkness is an order-1 invariant (which means that it is multiplied by λ if the vector field is multiplied by λ), we only have to prove $\text{Tks}(X_{p,q}, \Omega_{\text{Haar}}) = 2 \min(p, q)$ for p, q two coprime natural numbers.

Since every orbit of $X_{p,q}$ is periodic, we can consider a sequence $(K_n)_{n \in \mathbb{N}}$ of collections of periodic orbits whose induced normalized linear Dirac measures μ_n converge to Ω_{Haar} . We take K_n to be an n -component link all of whose components are torus knots $T(p, q)$. Actually K_n is a cabling with n strands on $T(p, q)$, so by Zupan's theorem [Zup12], the trunk of K_n is $2n \min(p, q)$. Since the period of each component of K_n is 1, the total length of K_n is n , and we get

$$\text{Tks}(X_{p,q}, \Omega_{\text{Haar}}) = \lim_{n \rightarrow \infty} \text{Tks}(X_{p,q}, \mu_n) = \lim_{n \rightarrow \infty} 2 \min(p, q) = 2 \min(p, q).$$

□

Proof of Theorem E. The previous computations show that for a Seifert flow $X_{\alpha,\beta}$ on \mathbb{S}^3 we have $\text{Hel}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = \alpha\beta$ and $\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = 2 \min(\alpha, \beta)$. There is no real function g such that $\min(\alpha, \beta) = g(\alpha\beta)$, so there is no function g such that $\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = g(\text{Hel}(X_{\alpha,\beta}, \Omega_{\text{Haar}}))$.

However the Seifert flows are not ergodic with respect to Ω_{Haar} . Indeed, the foliation of \mathbb{S}^3 by invariant tori is invariant, so that it is easy to construct an invariant set with arbitrary measure. Still, a theorem of Katok [Kat73] states that the vector field $X_{\alpha,\beta}$ can be perturbed (in the C^1 -topology) into an ergodic one. Starting from $X_{1,8}$ and $X_{2,4}$ and applying Katok's argument, we obtain two ergodic volume-preserving vector fields $X'_{1,8}$ and $X'_{2,4}$. By continuity, their trunknesses are close to 2 and 4 respectively, while their helicities are close to 8. At the expense of multiplying the $X'_{1,8}$ and $X'_{2,4}$ by a constant, we can assume that their helicities are exactly 8. However their trunknesses are still close to 2 and 4, hence different. □

The formula $\text{Tks}(X_{\alpha,\beta}, \Omega_{\text{Haar}}) = 2 \min(\alpha, \beta)$ is also interesting to compare with Kudryavtseva's and Encisco-Peralata-Salas-Torres de Lizaur's theorems: the function $(\alpha, \beta) \mapsto 2 \min(\alpha, \beta)$ is continuous but not differentiable, so that trunkness is a continuous vector field invariant, but it is not *integral regular* in the sense of [Kud16, EPT16].

4. TRUNKNESS AND THE EXISTENCE OF PERIODIC ORBITS

In this section we address the question of what happens when the infimum in the definition of the trunkness is a minimum, for non-singular vector fields on \mathbb{S}^3 with an invariant measure μ . We deduce that the vector field must possess an unknotted periodic orbit by finding a periodic orbit tangent to a level of the function. The proof of Theorem F in particular implies that there is height function h such that

$$\text{tks}_h(X, \mu) = \text{Flux}(X, \mu, h^{-1}(t_{\max}))$$

for some (not necessarily unique) $t_{\max} \in [0, 1]$ and such that all the connected components of $S = h^{-1}(t_{\max})$ along which X is tangent to S contain a periodic orbit of X . The existence of vector fields on \mathbb{S}^3 without periodic orbits [Kup94] implies that there are vector fields for which we cannot consider a minimum to define the trunkness.

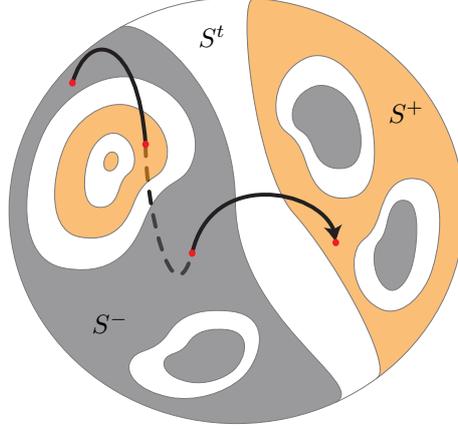


FIGURE 3. The decomposition of the level S of the height function into S^+ where X is positively transverse to S (orange), S^- where X is negatively transverse (black), and S^t where X is tangent to T (white). A piece of orbit of X that intersects S four times is also shown.

Proof of Theorem F. For f a height function we define

$$\begin{aligned} F_f : [0, 1] &\rightarrow \mathbb{R} \\ t &\mapsto \text{Flux}(X, \mu, f^{-1}(t)) \end{aligned}$$

Set h the height function such that $\text{Tks}(X, \mu) = \text{tks}_h(X, \mu)$ and let $t_{\max} \in [0, 1]$ be a maximum of F_h , hence

$$\text{Tks}(X, \mu) = \text{tks}_h(X, \mu) = \lim_{\epsilon \rightarrow 0} \frac{1}{\epsilon} \mu(\phi_X^{[0, \epsilon]}(h^{-1}(t_{\max}))).$$

Denote by S the level set $h^{-1}(t_{\max})$. Observe that the value t_{\max} is not necessarily unique.

We assume that \mathbb{S}^3 and S are oriented and thus we can distinguish three subsets of S (see Figure 3):

- S^t the closed set along which X is tangent to S ;
- S^+ the open set along which X is positively transverse to S ;
- S^- the open set along which X is negatively transverse to S .

We claim that none of these sets is empty. First assume that S^+ is empty, then $S = S^t \cup S^-$. Observe that $\mathbb{S}^3 \setminus S$ has two connected components that are diffeomorphic to open 3-dimensional balls. Hence there is one of these connected components, denote its closure by D , that is invariant under the diffeomorphism of \mathbb{S}^3 defined by ϕ_X^t for any $t > 0$, and since X is non-singular there exists $t_0 > 0$ such that $\Phi := \phi_X^{t_0}$ has no fixed points. Thus Φ maps D to D , and D is the closed 3-dimensional disc, hence by Brouwer fixed point theorem Φ has a fixed point, a contradiction. Thus S^+ is non-empty, and the same argument proves that S^- is non-empty. Now S^+ and S^- are open subsets of S and have empty intersection, hence $S^t = S \setminus (S^+ \cup S^-)$ is not empty.

Decompose $B := \partial S^t$ as $B = B^+ \cup B^-$, where B^+ and B^- are in the boundary of S^+ and S^- respectively. Observe that $B^+ \cap B^-$ is not necessarily empty and that there is at least one connected component of S^t whose boundary has both positive and negative parts.

Assume that X has no periodic orbits, then B is made of circles and each one of these circles is transverse to X in at least one point.

Lemma 4.1. *If a point p in S^t is such that either its positive or negative orbit is contained in S , then X has an unknotted periodic orbit.*

Proof. Assume without loss of generality that the positive orbit of p is contained in S , then it limits to some invariant set of X contained in S . By Poincaré-Bendixson Theorem such a set has

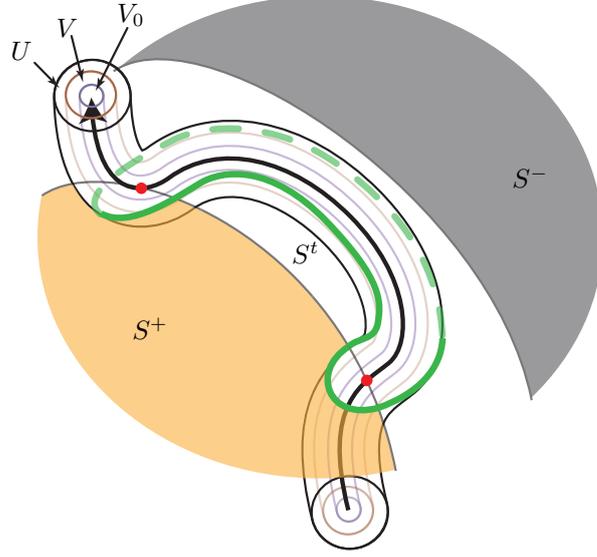


FIGURE 4. A neighborhood U of a piece of orbit \mathcal{O} of X that connects two points p, q in B^+ . The intersection of ∂U with S is bold and green.

to be a periodic orbit of X . Since the periodic orbit is contained in the sphere S it has to be unknotted. \square

Then under the assumption that X has no unknotted periodic orbits, we have that for every $p \in S^t$ the positive and negative orbit of p have to leave S at some point. Consider now two points $p, q \in B$ that are in the same orbit and such that the orbit segment connecting them is contained in S^t . We can thus assume that there exists $\tau \geq 0$ such that $\phi_X^\tau(p) = q$ and $\phi_X^s(p) \in S^t$ for all $0 \leq s \leq \tau$. Observe that by allowing τ to be zero, we consider the case $p = q$.

Take $\epsilon > 0$ and consider the orbit segment

$$\mathcal{O} = \{\phi_X^s(p) \mid -\epsilon < s < \tau + \epsilon\}.$$

The flowbox Theorem implies that there is a neighborhood U of \mathcal{O} and a diffeomorphism

$$\varphi : \mathbb{B}(1) \times (-\epsilon, \tau + \epsilon) \rightarrow U$$

so that the flowlines are the image under φ of the vertical segments $\{\cdot\} \times (-\epsilon, \tau + \epsilon)$. Here $\mathbb{B}(1)$ denotes the 2-dimensional open ball of radius 1.

Proposition 4.2. *There exists $p, q \in B$ as above such that $p \in B^-$ and $q \in B^+$ or $p \in B^+$ and $q \in B^-$.*

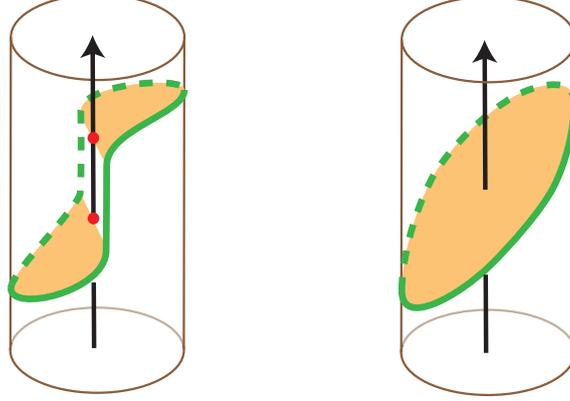
The idea of the proof is that if for every pair of points p, q as above that are both in B^+ or B^- , we can change the function h for another height function h_1 such that

$$\text{tk}_h(X, \mu) = \text{tk}_{h_1}(X, \mu)$$

and such that the level of h_1 realizing the trunkness has no tangent part that separates S^+ from S^- , which is impossible.

Proof. Consider a pair of points $p, q \in B^+$ as above (see Figure 4). Let V_0 be the neighborhood of \mathcal{O} defined as $\varphi(\mathbb{D}(1/3) \times (-\epsilon, \tau + \epsilon))$, where $\mathbb{D}(1/3)$ is the 2-dimensional closed disc of radius $1/3$ and $V = \varphi(\mathbb{B}(2/3) \times (-\epsilon, \tau + \epsilon))$. Hence $V_0 \subset V \subset U$. We will deform the levels of h intersecting V without changing the trunkness.

The image of S by φ^{-1} defines a surface Σ that is positively transverse to the vertical direction in $\mathbb{B}(1) \times (-\epsilon, 0)$ and $\mathbb{B}(1) \times (\tau, \tau + \epsilon)$, as in Figure 5 left. If we project Σ to $\mathbb{B}(1) \times \{0\}$, the flux

FIGURE 5. Modifying the levels of h in U around the arc pq in the case $p, q \in B^+$.

through Σ and through the image of Σ under the projection are the same. Thus if we change Σ (or any surface) for another surface whose projection, counted with multiplicities and signs, is the same as the one of Σ , the flux remains constant.

Inside $\mathbb{D}(1/3) \times (-\epsilon, \tau + \epsilon)$ we change the images under φ^{-1} of the levels of h to obtain a family of surfaces that are always positively transverse to X and are C^∞ -close to the original ones, in such a way that the projection to $\mathbb{B}(1) \times \{0\}$ is preserved (as in Figure 5 right). Using the neighborhood V , we can paste the deformed surfaces of V_0 with the original surfaces in $U \setminus V$.

Using φ this deformation can be pushed forward to the manifold so that the level surfaces of h that intersected V are modified and X is positively transverse to the surfaces inside V_0 . Let \tilde{S} be the surface obtained from S after the deformation and \tilde{h} be a height function whose level sets correspond to the deformed surfaces. Then

$$\text{tks}_h(X, \mu) = \text{tks}_{\tilde{h}}(X, \mu),$$

since $\text{Flux}(X, \mu, \tilde{S}) = \text{Flux}(X, \mu, S)$, and for every surface intersection V the corresponding equation holds. Clearly, the same proof works if $p, q \in B^-$.

Observe that the level \tilde{S} of \tilde{h} realizing the trunkeness coincides with S outside V . Moreover, the tangent part \tilde{S}^t of \tilde{S} is strictly smaller than S^t : the connected component A of S^t containing p and q got transformed into $A \setminus (V_0 \cap A)$. In other words there is now a strip across A .

Assume now that for any couple of points $p, q \in B$ that is joined by an orbit segment contained in S^t we have either $p, q \in B^+$ or $p, q \in B^-$. The sets \tilde{S}^t and B are compact, we can thus find a finite number of pairs of points $p, q \in B$ such that after deforming the levels h as above along each of the corresponding orbit segments, we obtain a height function h_1 such that

$$\text{tks}_h(X, \mu) = \text{tks}_{h_1}(X, \mu) = \text{Flux}(X, \mu, S_1),$$

where S_1 is the level of h_1 realizing the trunkeness and such that S_1^t is formed by discs. Hence none of the connected components of S_1^t separates the positively transverse set S_1^+ from the negatively transverse set S_1^- , a contradiction. \square

Consider now a pair of points p, q as in Proposition 4.2 and assume that $p \in B^-$ and $q \in B^+$. We now construct a height function h_2 such that

$$\text{tks}_h(X, \mu) > \text{tks}_{h_2}(X, \mu),$$

a contradiction that implies that X has unknotted periodic orbits.

Consider the function F_h and let M_h be the set of $t \in [0, 1]$ realizing the trunkeness, that is $M_h = \{t \in [0, 1] \mid F_h(t) = \text{tks}_h(X, \mu)\}$. Observe that M_h is closed. We distinguish two cases:

- (1) all the elements of M_h are isolated;

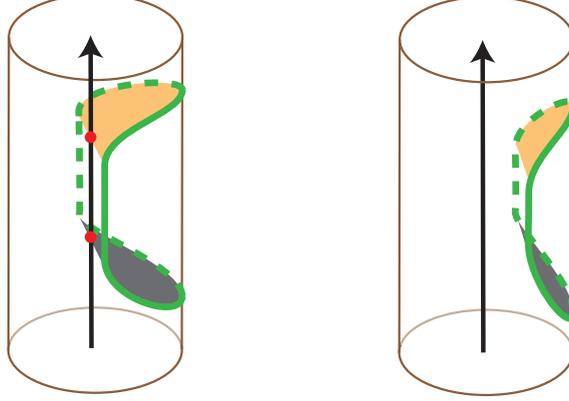


FIGURE 6. Modifying the levels of h in U around the arc pq in the case $p \in B^+$, $q \in B^-$.

(2) there exist a closed interval I_{\max} contained in M_h .

We start with the first case. Take $t_{\max} \in M_h$ and set $S = h^{-1}(t_{\max})$. To obtain h_2 we will deform the levels near S , if M_h has more than one element the following deformation has to be done near each corresponding level set. Thus we assume without loss of generality that t_{\max} is the only element of M_h .

Let \mathcal{O} , φ , U , V and V_0 be defined as above. Let $[a, b] \subset [0, 1]$ be such that $t_{\max} \in [a, b]$ and if $h^{-1}(t) \cap V_0 \neq \emptyset$ then $t \in [a, b]$. Shrinking V if necessary, we can assume that $\varphi(\mathbb{B}(2/3) \times (-\epsilon, \tau + \epsilon))$ is contained in $h^{-1}([a, b])$ and that for any $t \in [0, 1] \setminus [a, b]$ we have

$$\text{Flux}(X, \mu, h^{-1}(t)) < \text{tks}_h(X, \mu) - \delta,$$

for some $\delta > 0$. We assume also that $\varphi(\mathbb{B}(2/3) \times [0, \tau])$ is contained in $h^{-1}([a, b])$.

Consider now the surface Σ obtained as the image under φ^{-1} of S in U . Then either Σ is positively transverse to the vertical direction in $\mathbb{B}(1) \times (-\epsilon, 0)$ and negatively transverse to the vertical direction in $\mathbb{B}(1) \times (\tau, \tau + \epsilon)$, or it is negatively transverse to the vertical direction in $\mathbb{B}(1) \times (-\epsilon, 0)$ and positively transverse to the vertical direction in $\mathbb{B}(1) \times (\tau, \tau + \epsilon)$. We assume without loss of generality that Σ is negatively transverse to the vertical direction in $\mathbb{B}(1) \times (-\epsilon, 0)$ and positively transverse to the vertical direction in $\mathbb{B}(1) \times (\tau, \tau + \epsilon)$, as represented in Figure 6.

We want to deform the levels of h intersecting V_0 in such a way that their trace under the projection to $\mathbb{B}(1) \times \{0\}$ is reduced.

Shrinking V if necessary, we can assume that the level sets are:

- tangent or negatively transverse to X in $\varphi(\mathbb{B}(2/3) \times (-\epsilon, 0))$,
- tangent or positively transverse to X in $\varphi(\mathbb{B}(2/3) \times (\tau, \tau + \epsilon))$.

Consider the circle $C = \Sigma \cap \partial(\mathbb{D}(1/3) \times (-\epsilon, \tau + \epsilon))$. Since $\partial(\mathbb{D}(1/3) \times (-\epsilon, \tau + \epsilon))$ is topologically a sphere, C divides it into two discs. Let W be the disc that is entirely tangent to the vertical direction. There is a continuous deformation from Σ to the continuous surface $\tilde{\Sigma}$ that coincides with Σ outside $\mathbb{D}(1/3) \times (-\epsilon, \tau + \epsilon)$ and coincides with W in this set. Observe that the projection of $\tilde{\Sigma}$ to $\mathbb{B}(1) \times \{0\}$ is a proper subset of the projection of Σ . We can now approximate $\tilde{\Sigma}$ in $\mathbb{B}(2/3) \times (-\epsilon, \tau + \epsilon)$ with a smooth surface Σ_1 , that can be obtained from Σ by a continuous deformation that is the identity near the boundary of $\mathbb{B}(2/3) \times (-\epsilon, \tau + \epsilon)$.

Apply this deformation to nearby levels by pushing (to the right as in Figure 6) all the level sets intersecting $\mathbb{B}(1/3) \times (0, \tau)$ with a continuous map that is the identity near the boundary of $\mathbb{B}(2/3) \times (-\epsilon, \tau + \epsilon)$. By construction the projection to $\mathbb{B}(1) \times \{0\}$ of the image under φ^{-1} of any level set intersecting V is a subset of the original one and for levels sufficiently near $h^{-1}(t_{\max})$ it is a proper subset. Thus the flux of X gets reduced on any of the deformed surfaces.

As before, we use φ to push forward the deformation to \mathbb{S}^3 and obtain the levels of a new height function h_2 such that $\text{tks}_{h_2}(X, \mu) < \text{tks}_h(X, \mu)$.

The proof of the case where M_h has only isolated elements ends here and we are left with the case where the set M_h contains an interval $I_{\max} = [a, b]$. Take $t_{\max} = a$ and use the previous procedure to obtain a new height function h_2 such that the interval I_{\max} is reduced to $I_2 = [a_2, b]$ for some $a_2 > a$. This process can be applied as long as the boundary of the tangent part of $h^{-1}(t)$ for any $t \in [a, b]$ is not composed by periodic orbits of X . Recursively either we find an unknotted periodic orbit or we obtain a height function f such that $\text{tks}_f(X, \mu) < \text{tks}_h(X, \mu)$ as needed. \square

The proof of Theorem F gives the following result.

Corollary 4.3. Let X be a non-singular vector field on \mathbb{S}^3 , μ an invariant measure and h a height function such that

$$\text{Tks}(X, \mu) = \text{tks}_h(X, \mu).$$

Then there is a height function h_1 such that:

- $\text{tks}_h(X, \mu) = \text{tks}_{h_1}(X, \mu)$;
- for every $s \in [0, 1]$ such that $\text{tks}_{h_1}(X, \mu) = \text{Flux}(X, \mu, h_1^{-1}(s))$ and for every point p in the boundary of the tangent part of $S = h_1^{-1}(s)$, either p belongs to a periodic orbit or its orbit limits to a periodic orbit. In both cases the periodic orbit is contained in S and is thus unknotted.

One may wonder whether the converse of Theorem F is true, namely if the existence of an unknotted periodic orbit for a μ -preserving vector field X implies that there is a height function that achieves the trunkeness $\text{Tks}(X, \mu)$. We believe that it is not the case as we explain below:

Claim 4.4. There exists a non-singular vector field X on \mathbb{S}^3 preserving the standard volume, admitting an unknotted periodic orbit, and such that for every height function h one has $\text{Tks}(X, \mu) < \text{tks}_h(X, \mu)$.

We do not provide a complete proof as this would make the paper much longer and we do not believe the statement justifies it. However the construction relies on the following remark that may be of independent interest: inserting a volume-preserving plug does not change the trunkeness. Indeed it changes a set of orbits of volume zero, so that approximating the vector field by longer and longer orbits that are not trapped shows that the trunkeness is unchanged.

Sketch of proof. Take $Y_0 = X_{\alpha, \beta}$ a Seifert vector field with α/β irrational and $\beta < \alpha$. Hence $\text{Tks}(Y_0, \Omega_{\text{Haar}}) = 2\beta$. Let U be a flowbox around the orbit $z_2 = 0$. We deform Y_0 into a continuous family Y_s with $s \in [0, 1]$ by changing Y_0 inside U so that the volume is preserved and the trunkeness is unchanged, in such a way that

- Y_s for $s \neq 1$ has two unknotted periodic orbits and the trunkeness is a minimum;
- Y_1 has three unknotted periodic orbits and there is no function that realizes the trunkeness.

We do this by inserting inside U a family of volume-preserving Wilson plugs W_s [Kup96]: W_0 does nothing, $W_s, s \neq 1$, deforms the flow by isotopy by twisting the orbits first in one direction and then in the other, and finally W_1 traps a certain circle C . We pay attention that the orbit $z_2 = 0$ intersects W_s for every s and it intersects C for $s = 1$.

Since the family is continuous and realizes a volume-preserving isotopy for $s < 1$, the trunkeness is unchanged and realized by the image of h by the isotopy used in the family of plugs, for h as in Section 3. By continuity, the trunkeness is unchanged also for $s = 1$, thus $\text{Tks}(Y_s, \Omega_{\text{Haar}}) = 2\beta$ for every $s \in [0, 1]$.

Now the sphere $h^{-1}(1/2)$, that realizes the trunk for all values $s < 1$ explodes at $s = 1$, that is $\text{tks}_h(Y_1, \Omega_{\text{Haar}}) > 2\beta$. Suppose that another function h' realizes the trunk at $s = 1$, then it would not be far from realizing the trunk for $s < 1$, so the level with maximum flux would have to be tangent to the periodic orbit containing the arc $z_2 = 0$ in the complement of U , but such a sphere has flux strictly bigger than 2β for $s = 1$. \square

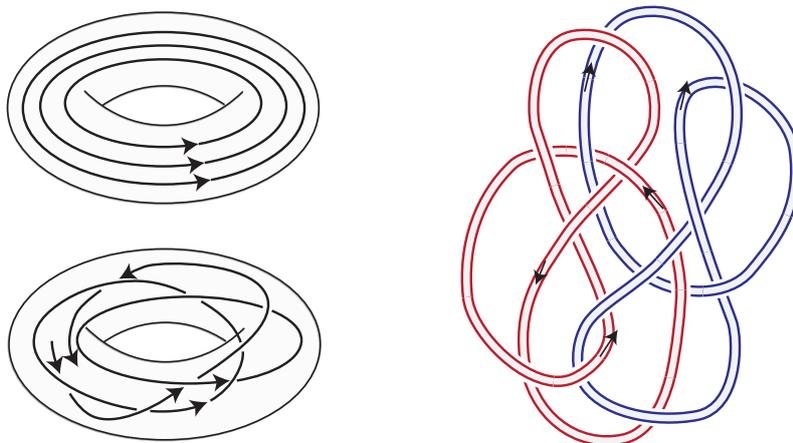


FIGURE 7. On the left, two vector fields supported on the unlink and both transverse to the canonical meridian discs. The top one has all its orbits horizontal, hence its trunkness is 0 while the bottom one has linked orbits. Its trunkness is at most $2 \cdot \text{Flux}(X, \Omega, D)$ but it might be smaller. On the right a vector field supported on a link L both of which components are figure-eight knots. If the flux of the vector field through the canonical meridian discs of both components is equal to F , then the trunkness of this vector field is $F \cdot \text{Tk}(L) = 8F$ by Proposition 5.1.

5. TRUNKENNESS OF KNOTTED TUBES

In this section we compute the trunkness with respect to a volume form of some vector fields supported in a tubular neighborhood of a link or knot. Our statement is reminiscent from Zupan's theorem [Zup12] concerning the trunk of the cable of a knot. Recall that for a divergence-free vector field supported on a tube, the fluxes through all meridian discs are equal.

Proposition 5.1. (see Figure 7 right) *Suppose that X is a Ω -preserving vector field supported on tubes T_1, \dots, T_j that are tubular neighborhoods of knots k_1, \dots, k_j , each knot k_i being non-trivial, and such that X is transverse to all canonical meridian discs and the flux of X through each of them is constant equal to some $F \neq 0$, then we have*

$$\text{Tks}(X, \Omega) = F \cdot \text{Tk}(k_1 \cup \dots \cup k_j).$$

Note that the trunkness in this case is independent from the dynamics of X inside each tube, and in particular of the first-return map on a meridian disc, exactly like the trunk of a cable link is independent of the twist number of the cabling. However the restriction that all the knots k_i are non-trivial is necessary. Indeed the trunkness of a vector field supported on a tube that forms a trivial knot may be smaller than $2F$. For example take an unknotted solid torus in \mathbb{R}^3 that supports a vector field obtained by the suspension of the identity (with no extra twist) and assume that the vector field is zero outside the solid torus (see Figure 7 top left). The trunkness of such vector field is zero: it is enough to consider a height function whose levels are always tangent to the vector field. Observe that the levels of such a height function intersect the solid torus along circles or annuli. As this example shows, the trunkness of a vector field supported in the neighborhood of a link with at least one unknotted component seems hard to determine (see Figure 7).

Proof. Let $L = k_1 \cup k_2 \cup \dots \cup k_n \subset \mathbb{S}^3$ be a link all of whose components are non-trivial knots. Let h be a height function such that $\text{Tk}(L) = \text{tk}_h(L)$. Observe that we can assume that h exists since for a knot or link the trunk is defined by a minimum (see Definition 1.1). The trunk of L is then realized by one or more level sets of h , that is, there exist t_1, t_2, \dots, t_k such that for any $1 \leq i \leq k$ there is a critical value c_i of $h|_L$ so that $t_i < c_i < t_{i+1}$ and $\text{Tk}(L) = \#\{L \cap h^{-1}(t_i)\}$. Let

$$m_j(t_i) = \#\{k_j \cap h^{-1}(t_i)\}, \quad \text{for } 1 \leq j \leq n \quad \text{and} \quad 1 \leq i \leq k.$$

For any $0 < \epsilon < 1$ there is an Ω -preserving diffeomorphism f_ϵ of \mathbb{S}^3 that makes the solid tori T_j longer and of radius ϵr_j for any $1 \leq j \leq n$, with r_j the radius of the tubular neighborhood T_j . Let X_ϵ be the vector field obtained from X via f_ϵ , then $\text{Tks}(X, \Omega) = \text{Tks}(X_\epsilon, \Omega)$ for every ϵ .

Assume that there is a height function g and an index i such that $\text{tks}_g(X, \Omega) < F \cdot \sum_{j=1}^n m_j(t_i)$. Consider the height function $g_\epsilon = g \circ f_\epsilon^{-1}$, then Theorem A implies $\text{tks}_g(X, \Omega) = \text{tks}_{g_\epsilon}(X_\epsilon, \Omega)$ and

$$\text{tks}_{g_\epsilon}(X_\epsilon, \Omega) < F \cdot \sum_{j=1}^n m_j(t_i).$$

We claim that $\text{tk}_{g_\epsilon}(L) < \sum_{j=1}^n m_j(t_i) = \text{Tk}(L)$ holds, which is absurd.

Assume first that g_ϵ restricted to the core of the tori $f_\epsilon(T_j)$ is a Morse function. The core of the tori form the link L thus $\text{tk}_{g_\epsilon}(L) \geq \text{Tk}(L)$ in one hand. But since

$$\text{tks}_{g_\epsilon}(X_\epsilon, \Omega) = \text{Flux}(X_\epsilon, \Omega, g_\epsilon^{-1}(T)) < F \cdot \min_{1 \leq i \leq k} \sum_{j=1}^n m_j(t_i)$$

for some $T \in [0, 1]$, taking ϵ arbitrarily small tells us that the number of discs in the intersection of $g_\epsilon^{-1}(T)$ and the tori is smaller than $\text{Tk}(L)$. In other words we conclude that $\text{tk}_{g_\epsilon}(L) < \text{Tk}(L)$, which is impossible. We are left with the case where g_ϵ is not a Morse function when restricted to L , seen as the core of the tori $f_\epsilon(T_j)$. The following lemma finishes the proof of the proposition.

Lemma 5.2. *In the previous context, there exists another height function g''_ϵ so that:*

- $g''_\epsilon|_L$ is a Morse function;
- $\text{tks}_{g_\epsilon}(X_\epsilon, \Omega) = \text{tks}_{g''_\epsilon}(X_\epsilon, \Omega)$.

Proof. Let $S = g_\epsilon^{-1}(t)$ be a level that is tangent to at least one of the components of L and let k_1 be one of the tangent components. We will modify g_ϵ in a neighborhood of k_1 , this modification taking place near the part of k_1 that is tangent to S .

Observe that S is tangent to a closed subinterval of k_1 , since if it were tangent to all of k_1 then k_1 would be the trivial knot, in contrary to our assumption on L . For $\delta < \epsilon r_1$, consider $N(\delta, k_1)$ the δ -tubular neighborhood of k_1 that is contained in $f_\epsilon(T_1)$. For δ sufficiently small, the intersection $S \cap N(\delta, k_1)$ is composed by a finite number of discs. Let D_1 be one of these discs, then ∂D_1 is included in $\partial N(\delta, k_1)$ and is either a contractible circle in $\partial N(\delta, k_1)$ or not.

If ∂D_1 is contractible in $\partial N(\delta, k_1)$, then we can locally deform the levels of g_ϵ near D_1 , to obtain a new height function g'_ϵ such that:

- the disc D'_1 obtained from D_1 is tangent to k_1 at one point;
- near D'_1 all levels are transverse to k_1 ;
- $\text{tks}_{g_\epsilon}(X_\epsilon, \Omega) = \text{tks}_{g'_\epsilon}(X_\epsilon, \Omega)$.

The support of the deformation is contained in $N(\delta, k_1)$. Performing this deformation near any disc in $S \cap N(\delta, k_1)$ whose boundary is contractible in $\partial N(\delta, k_1)$, we can assume now that the discs of S that are tangent to k_1 have non-contractible boundary in $\partial N(\delta, k_1)$. Thus these discs are homologous to meridional discs $\mathbb{D}^2 \times \{\theta\}$ of T_1 . Again, we can locally deform the levels, so that this discs are transverse to k_1 . The deformed height function g''_ϵ is Morse when restricted to L .

Thus g''_ϵ is Morse when restricted to k_1 . Repeating this process if necessary, we obtain that g''_ϵ is Morse when restricted to L . □

□

REFERENCES

- [Arn73] ARNOLD Vladimir I.: The asymptotic Hopf invariant and its applications. *Proc. Summer School in Diff. Equations at Dilizhan*, 1973 (1974), Evevan (in Russian); English transl. *Sel. Math. Sov.* **5** (1986), 327–345.
- [AK98] ARNOLD Vladimir I. and KHESIN Boris: *Topological methods in hydrodynamics*, Appl. Math. Sci. **125**, Springer (1998).
- [Baa11] BAADER Sebastian: Asymptotic concordance invariants for ergodic vector fields, *Comment. Math. Helv.* **86** (2011), 1–12.

- [BM12] BAADER Sebastian and MARCHÉ Julien: Asymptotic Vassiliev invariants for vector fields, *Bull. Soc. Math. France* **140** (2012), 569–582.
- [EPT16] ENCISO Alberto, PERALTA-SALAS Daniel and TORRES DE LIZAUR Francisco: Helicity is the only integral invariant of volume-preserving transformations, *Proc. Natl. Acad. Sci. USA* **113** (2016), 2035–2040.
- [FH91] FREEDMAN Michael H. and HE Zheng-Xu: Divergence-Free Fields: Energy and Asymptotic Crossing Number, *Ann. of Math.* **134** (1991), 189–229.
- [Gab87] GABAI David: Foliations and the topology of 3-manifolds III, *J. Differential Geom.* **26** (1987), 479–536.
- [GG01] GAMBAUDO Jean-Marc and GHYS Étienne: Signature asymptotique d’un champ de vecteurs en dimension 3, *Duke Math. J.* **106** (2001), 41–79.
- [Hel1858] VON HELMHOLTZ Hermann: Über Integrale der hydrodynamischen Gleichungen, welche den Wirbelbewegungen entsprechen, *J. Reine Angew. Math.* **55** (1858), 25–55.
- [Kat73] KATOK Anatole B.: Ergodic perturbations of degenerate integrable Hamiltonian systems, *Math. USSR Izv.* **7** (1973), 535.
- [Kud14] KUDRYAVTSEVA Elena A.: Conjugation invariants on the group of area-preserving diffeomorphisms of the disk, *Math. Notes* **95** (2014), 877–880.
- [Kud16] KUDRYAVTSEVA Elena A.: Helicity is the only invariant of incompressible flows whose derivative is continuous in C^1 -topology, *Math. Notes* **99** (2016), 611–615.
- [Kup94] KUPERBERG Krystyna: A smooth counterexample to the Seifert conjecture, *Ann. of Math.* **140** (1994), 723–732.
- [Kup96] KUPERBERG Gregory: A volume-preserving counterexample to the Seifert conjecture, *Comment. Math. Helv.* **71** (1996), 70–97.
- [Mof69] MOFFATT Keith: The degree of knottedness of tangle vortex lines, *J. Fluid. Mech.* **106** (1969), 117–129.
- [Mor61] MOREAU Jean-Jacques: Constantes d’un îlot tourbillonnaire en fluide parfait barotrope., *C. R. Acad. Sci. Paris* **252** (1961), 2810–2812.
- [Mor00] MORGAN Frank: *Geometric measure theory. A beginner’s guide*, Third edition. Academic Press, Inc., San Diego, CA (2000).
- [Ozw10] OZAWA Makoto: Waist and trunk of knots, *Geom. Dedicata* **149** (2010), 8594.
- [Tai1877] TAIT Peter Guthrie: On knots, *Trans. Roy. Soc. Edin.* **28** (1877), 145–190.
- [Tho1867] THOMSON William: On Vortex Atoms, *Proc. Roy. Soc. Edinburgh* **6** (1867), 94–105; reprinted in *Phil. Mag.* **34** (1867), 15–24.
- [Vog02] VOGEL Thomas: On the asymptotic linking number, *Proc. Amer. Math. Soc.* **131** (2002), 2289–2297.
- [Wol58] WOLTJER Lodewijk: A Theorem on Force-free magnetic Fields, *Proc. Natl. Acad. Sci. USA* **44** (1958), 489–491.
- [Zup12] ZUPAN Alexander: A lower bound on the width of satellite knots, *Topology Proc.* **40** (2012), 179–188.