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The nonwandering set of flows on a Reeb foliation

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THE NONWANDERING SET OF FLOWS ON A REEB FOLIATION

1 - INTRODUCTION

Let $\chi(S^3)$ be the space of the C^r vector fields, $r \geq 4$, tangent to a Reeb foliation σ on the sphere S^3 [1] with the usual C^r topology.

A periodic orbit α (in particular a singular point) of $X \in \chi(S^3)$ is called *hyperbolic* if it is hyperbolic in the usual sense for the restriction $X|F_p$ where F_p denotes the leaf of σ containing $p \in \alpha$. When α is a singular point or is the boundary of a disc contained in its leaf, the qualitative behaviour of small perturbations of the vector field X is given by the Kupka-Smale theorem. Let α_1, α_2 be generators of the fundamental group of the compact leaf T^2 and $H(\alpha_i)$ the holonomy given by

$$\begin{cases} g_1(y) = y, & y \leq 0 \\ g_1(y) < y, & y > 0 \end{cases} \quad \text{and} \quad \begin{cases} g_2(y) > y, & y < 0 \\ g_2(y) = y, & y \geq 0. \end{cases}$$

Suppose $\alpha_X \subset T^2$ a hyperbolic periodic orbit attractor for $X|T^2$. When α_X is homotopic to α_1 there exists an open neighborhood V of α_X in S^3 such that the periodic orbits of small perturbations $Y \in \chi(S^3)$ of the vector field X with points in V have the same type of α_X, are contained in V and define a cylinder with boundary $\alpha_Y \subset T^2$ which is the ω_Y-limit of all the points $p \in V$. If α_X is homotopic to α_1^{-1} the periodic orbits of Y which are completely contained in V define a cylinder with boundary $\alpha_Y \subset T^2$ which is an attractor except for α_Y which also admits a 2-dimensional invariant and unstable manifold. When α_X is homotopic to $\alpha_1^m\alpha_2^n$, $mn \neq 0$, α_Y is the only periodic orbit completely contained in V. A hyperbolic periodic orbit $\alpha_X \subset T^2$ which is an attractor for $X|T^2$ is called a *saddle type orbit* if it is homotopic to $\alpha_i^m\alpha_j^n$, $m \leq 0$ with $n < 0$ if $m = 0$.

A *saddle connection* is a regular trajectory $\gamma \subset T^2$ whose α and ω limit sets are saddle, saddle node or saddle type orbit and is not interior to the 2-dimensional invariant manifold of the saddle node.

The periodic orbits which are quasi-generic [3] in their own leaves and the saddle connections, with $\mathrm{trace} DX|F_p(p) \neq 0$ in the loop at p [3], are called *quasi generic elements* if they are generic respect the local parameter of leaves. The structure of orbits locally in the quasigeneric orbits and in the connections between singular points are given in [3]

In [4] was considered a residual set G_2 in $X(S^3)$ of vector fields such that only the saddle connections between singular points are generic respect the local parameter of the leaves. There was given also an open proper subset of $X(S^3)$ of vector fields without saddle type orbit where the vector fields without Ω-explosion are dense.

In this work we are allowing for the saddle type orbits and all the types of saddle connections. We define a dense set G_3 in $X(S^3)$ of vector fields such that all the saddle connections are quasigeneric elements and conclude the density of the vector fields without Ω-explosion in the entire space $X(S^3)$.

Now we state the main results of this work whose proofs will be outlined in the subsequent parts.

Theorem: There exists G_3, a dense set of vector fields $X \in \mathcal{X}(S^3)$ such that:

a) $X|_{T^2}$ is Morse-Smale

b) the periodic orbits are hyperbolic or quasi-generic

c) the saddle connections are quasi-generic

d) each leaf of σ contains at most one quasi-generic element

Corollary: There exists in $\mathcal{X}(S^3)$ a dense set of vector fields without Ω-explosion.

2. PROOF OF THEOREM

Consider $\mathcal{X}(S^3) \supset G_1 \supset G_2(T) \supset G_2(T;S)$ each open and dense in the preceding, already described in [4] :

G_1 denotes a set of vector fields $X \in \mathcal{X}(S^3)$ whose singular points are hyperbolic but for a finite number of quasi-generic points, $X|T^2$ is a Morse-Smale vector field and each leaf of σ contains at most one quasi generic singular point.

$G_2(T)$ denotes a set of vector fields $X \in G_1$ whose periodic orbits with period $\leq T$ are hyperbolic or quasi-generic and each leaf contains at most one quasi-generic periodic orbit with period τ, $0 \leq \tau \leq T$.

$G_2(T,S)$ denotes a set of vector fields $X \in G_2(T)$ without saddle connection between saddle node and saddle type orbit, whose saddle connection between singular points with length $\leq S$ are quasi-generic and lie at most one in each leaf with the additional condition that the quasi-generic periodic orbits of such a leaf have period $> T$.

Take $X \in G_1$ and $\alpha_i (i=1,2, \ldots, n)$ its saddle type orbits. Consider open neighborhoods V^i of α_i and $\mathfrak{V}$ of X in G_1 such that $\overline{V}^i \cap \overline{V}^j = \phi$, $Y \in \mathfrak{V}$ admits, for each i, only one saddle type orbit $\alpha_i(Y) \subset V^i$, of the same type of α_i, that is the only orbit completely contained in $\overline{V}^i$ except for the local cylinder of hyperbolic orbits at $\alpha_i(Y)$. We fix the neighborhoods V and $\mathfrak{V}$ and suppose $\alpha_i(Y)$ to be the only periodic orbits of $Y|_{T^2}$ at V.

Let $\gamma \not\subset V$ be a trajectory of $Y \in \mathfrak{V}$, $t_1 = \inf \{t \in R: \forall s \geq t, \gamma(s) \in V\}$ and $t_2 = \sup \{t \in R: \forall s \leq t, \gamma(s) \in V\}$. The length of $\gamma(t)$ with $-\infty \leq t_2 < t < t_1 \leq \infty$ will be denoted *length* γ. For $\gamma \subset V$, *length* γ is zero.

Fixed X,V and $\mathfrak{V}$ we can suppose the existence of a number $0 < m < 1$ and an open $A \subset S^3$, $\overline{A} \cap \overline{V} = \phi$ containing the singular points of any $Y \in \mathfrak{V}$ such that the saddle node separatrices, the orbits on the central manifold of saddle type orbit and the saddle separatrices not completely contained in A have *length* $\geq m$.

Given T,S,R > 0 we denote by $\mathfrak{D}(X,T,S,R)$ the set of all the vector fields $Y \in \mathfrak{D} \cap G_2(T,S)$ whose connections between saddle and saddle type orbit with *length* $\leq$ R are quasi-generic and lie at most one in each leaf with the additional condition that the quasi-generic saddle connections between critical points and the quasi-generic periodic orbits of such a leaf have length > S and period > T respectively.

Proposition 1: $\mathfrak{D}(X,T,S,R)$ is open and dense in $\mathfrak{D}$ when $1 \leq R < S$

Lemma 1: Take $X \in G_1$ and $p \notin T^2$

a) $\omega(p)$ is a cycle when $\omega(p) \subset F_p$

b) $\omega(p)$ is a periodic orbit or contains a saddle type orbit when $\omega(p) \cap T^2 \neq \phi$

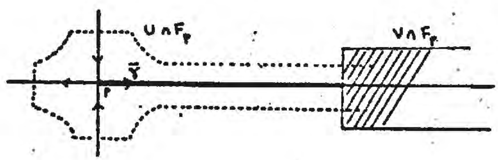
c) $\alpha(p)$ is a saddle type orbit γ when $\omega(p)$ is a saddle type orbit and $\alpha(p) \supset \gamma$

Lemma 2: Take $Y \in \mathfrak{D}$, $p \notin T^2$ and γ a non trivial periodic orbit such that $\gamma \subset \omega(p)$. Then, for each R > 0, there exist neighborhoods $V_p \subset S^3 - T^2$ of p and $\mathfrak{D}_p \subset \mathfrak{D}$ of Y such that any regular orbit of $Z \in \mathfrak{D}_p$, but eventually for those in central manifold of saddle type orbit, at V_p have *length* > R.

Lemma 3: If $Y \in \mathfrak{D}(X,T,S,R)$ and $0 < R \leq S$ then Y admits a finite number of connections between saddle and saddle type periodic orbit with *length* $\leq$ R.

Proof: If there were a infinite number of such connections γ_n between saddles p_n, with $p_n \to p$, and a saddle type periodic orbit α we would have a chain of saddle connections with lengths $\leq R \leq S$ in the leaf F_p. □

Take $Y \in \mathfrak{D}(X,T,S,R)$ and $\gamma = \gamma(Y)$ a connection between a saddle $p \notin T^2$ and a saddle type orbit α with $\omega(\gamma) = \alpha$ and *length* $\gamma \leq R$. Denote $\overline{\gamma} = \overline{\{\gamma(t) : -\infty < t \leq t_1\}}$ (see definition of *length* γ). Consider open neighborhoods U of $\overline{\gamma}$ and $\mathfrak{U}$ of Y in $\mathfrak{D} \cap G_2(T,S)$ such that $Z \in \mathfrak{U}$ admits only one connection $\gamma(Z)$ between saddle and saddle type orbit, with $\overline{\gamma(Z)} \subset U$, which is quasi generic. Furthermore, the *length* $o_Z(x)$, with $x \in U - \gamma(Z)$ and $o_Z(x) \cap V \neq \phi$, is greater than R. For $Z \in \mathfrak{U}$ we also suppose that in the saturated set of U by the foliation the periodic orbits with period $\leq$ T are hyperbolic and the saddle connections between singular points have length > S.



Proof of proposition 1: For $Y \in \mathfrak{D}(X,T,S,R)$ consider, like above, convenient neighborhoods U^i and $\mathfrak{U}^i$ determined by the connections between saddle and saddle type orbit with length $\leq R$. The continuity of arc length, the lemmas above and the local behaviour in the saddle, saddle-node and saddle connections between singular points with length $\leq R < S$ [2], [3] guarantee the existence, for each $x \in K = S^3 - V - \bigcup U^i$ of open neighborhoods U_x of x and $\mathfrak{U}_x$ of Y in $\mathfrak{D} \cap G_2(T,S)$ such that the connections between saddle and saddle type orbit, of $Z \in \mathfrak{U}_x$, by U_x have *length* $> R$. The openness follows from the compacity of K. The density will follow like proposition II-2.3 of [3]. Let $\alpha_i(Y)$ be the saddle type orbits of $Y \in \mathfrak{D} \cap G_2(T,S)$ and D_i the fundamental domain of the Poincaré map associated to $\alpha_i(Y)$ with $D^i \cap T^2 = \phi$. Consider for $\ell > 0$ the compact $K_\ell = \{x \in \bigcup \overline{D_i} : o_Y(x)$ is saddle-separatrix with *length* $\leq \ell\}$. For $x \in K_\ell, o_Y(x) = \gamma$, $\omega(x) = \alpha_i(Y)$, $\alpha(x) = p$, consider the above neighborhoods U, $\mathfrak{U}$ such that for $Z \in \mathfrak{U}$ the connections between saddle $q \notin U$ and $\alpha_i(Z)$ by $\overline{U} \cap \overline{V}$ have *length* $> \frac{2}{3}$ *length* $\gamma + m$ (m in the beginning of this section) and the connections between saddle and $\alpha_j(Z)$ by $\overline{U} \cap \overline{V}$ have *length* $> \max(S, (\frac{4}{3})^k m)$ where k is a natural number > 1 such that $(\frac{4}{3})^{k-1} m \leq$ $\leq R < (\frac{4}{3})^k m$. Beginning with $\ell = \frac{4}{3} m$, cover the compact $\overline{D}_i \cap K_\ell$ with a finite number of open U_s^i such that $(\bigcup \overline{U}_s^i) \bigcap_{i \neq j} (\bigcup \overline{U}_s^j) = \phi$. For each i we perturbe the vector field in these neighborhoods without change in $S^3 - \cup U_s^i$ to have a finite number of connections between $\alpha_i(Y)$ and saddle point with *length* $\leq \ell = \frac{4}{3}$ m, which are quasi-generic. By a small change we obtain a vector field Z with, at most, one such connection in each leaf where the saddle connections between critical points have length > S and the periodic orbits with period $\tau, 0 \leq \tau \leq T$ are hyperbolic. For each connection γ_i between saddle and saddle type orbit $\alpha_i(Z)$ with *length* $\leq \frac{4}{3}$ m consider the neighborhoods U^i such that $\overline{U}^i \cap \overline{U}^j = \phi$, the connections between saddle and α_j $(i \neq j)$ by $\overline{U}^i \cap \overline{V}$ have *length* > max $(S, (\frac{4}{3})^k$ m) and between saddle $q \notin U^i$ and α_i, have *length* $> S + \frac{2}{3}$ m $> (\frac{4}{3})^2$ m since the connections between saddles and between saddle and saddle node in F_{γ_i} have *length* > S. Repeat the initial process for $\ell = (\frac{4}{3})^2$m perturbing the connections between saddle and saddle type orbit of *length* τ, $\frac{4}{3}$ m $< \tau \leq (\frac{4}{3})^2$m without breaking the initial perturbation; thus successively until $\ell = (\frac{4}{3})^k$m. □

Given L>0 we call $\mathfrak{D}(X,T,S,R,L)$ the set of the vector fields $Y \in \mathfrak{D}(X,T,S,R)$ whose connections between two saddle type orbits with *length* $\leq$ L are quasi generic and lie at most one in each leaf with the additional condition that the quasi-generic periodic orbits, the saddle connections between singular points and between saddle and saddle type orbit of such a leaf have period > > T, *length* > S and > R respectively.

Lemma 4: Let $Y \in \mathfrak{D}(X,T,S,R,L)$ and $0<L\leq R\leq S$. Then Y has a finite number of connections between saddle type orbits with *length* $\leq L$.

Proposition 2: $\mathfrak{D}(X,T,S,R,L)$ is open and dense in $\mathfrak{D}(X,T,S,R)$ for $1\leq L\leq R<S$.

Proof: Take $Y \in \mathfrak{D}(X,T,S,R)$ and keep notation of the proof of proposition 1. Consider the compact $F = \{x \in \cup \overline{D}_i : o_Y(x)$ is a connection between saddle type orbits with *length* $\leq L\}$. Call $\alpha_j(Y)$ the saddle type orbits which are attractor sets on T^2. For each $x \in K \cap \overline{D}_j$ consider convenient open neighborhoods $U^j \subset S^3 - V$ of a segment of $o_Y(x)$ and $\mathfrak{U}^j$ of Y in $\mathfrak{D}(X,T,S,R)$ such that if $\alpha(x) = \alpha_j(Y)$ and $\omega(x) = \alpha_{k_j}(Y)$, then, any trajectory by $\overline{U}^j$ not connecting $\alpha_j(Z)$ and $\alpha_{k_j}(Z)$, has *length* $> L$. From the compacity of $F \cap \overline{D}_i$ we have a finite number of such neighborhoods U^j_k with $(\cup \overline{U}^j_k) \bigcap_{i\neq j} (\cup \overline{U}^i_k) = \phi$. Begin changing the vector field in $\cup U^1_k$ such that any connection between $\alpha_1(Y)$ and saddle type orbit with *length* $\leq L$ is quasi generic. Repeating the process for $j = 2,3, \ldots$ we have a vector field whose saddle type orbits admit only a finite number of such connections. For a small change we have a vector field in $\mathfrak{D}(X,T,S,R,L)$. □

The theorem follows by considering

$$G_3 = \bigcup_{X \in G_1} \Big(\bigcap_{m,n \in N^*} \mathfrak{D}(X,m,n+2,n+1,n)\Big)$$

3. ON THE NONWANDERING SET

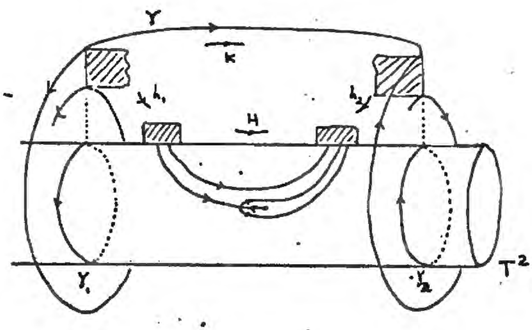
Let γ be a quasi-generic connection between two saddle type periodic orbits γ_1, γ_2 of $X \in G_1$ with $\omega(\gamma) = \gamma_1$, $\alpha(\gamma) = \gamma_2$. Call P_1, P_2 the Poincaré maps of $X,(-X)$ associated to γ_1 and γ_2 respectively. In coordinates (see [5]) we have $P_1(x,y,X) = (\lambda_1 x, g_X(y))$, $P_2(x,y,X) = (\lambda_2 x, g_X(y))$ where $g_X \in C^\infty$, $g_X(0) = g_X^{(n)}(0) = 0$ for $n>1$, $g_X'(0) = 1$. Suppose $\lambda_1 > \lambda_2 > 1$ then $g_X(y) < y$ for $y > 0$.

For $x>0$ small enough and $y \in]g_X(1), 1]$ define $h_1(x,y,X) = (\lambda_1^{n_1(x,y,X)} x, \; g_X^{n_1(x,y,X)}(y))$ where $0 < a \leq \lambda_1^{n_1(x,y,X)} x < \lambda_1 a$

$h_2(x,y,X) = (\lambda_2^{n_2(x,y,X)} x, \; g_X^{n_2(x,y,X)}(y))$ where

$0 < a \leq \lambda_2^{n_2(x,y,X)} x < \lambda_2 a$

Suppose $a = 1$.



The next results stated for X are obviously extended for a neighborhood of X in G_1.

Lemma 5: Under the above conditions, $\pi_2 h_1(x,y,X) > \pi_2 h_2(x,y,X)$ for $x>0$ small enough and $y \in \left] g_X(1),1 \right]$ where $\pi_2(x,y) = y$.

Proof: Given a natural $N>0$ we have $n_2(x,y,X)-n_1(x,y,X)>N$ for small $x>0$ and $y \in \left] g_X(1),1 \right]$ since $\frac{\ell n\ 1/x}{\ell n\ \lambda_i} \leq n_i(x,y,X) < \frac{\ell n\ \lambda_i/x}{\ell n\ \lambda_i}$, $i = 1,2$. □

Suppose $p \in T^2$, $\alpha(p) = \gamma_1$, $\omega(p) = \gamma_2$. On certain open subsets of $\{(x,y): x>0,\ y \in \left] g_X(1),1 \right]\}$, we can define Hh_1, h_2K where H and K are given by the flows of X and (-X) respectively. With the notation of lemma 5 we have

$$-1 < n_2(x,y,X)-n_2(K(x,y),X) - \frac{\ell n\ K_1(x,y)\ /x}{\ell n\ \lambda_2} < 1$$

where $K_1(x,y) = \pi_1 K(x,y)$. From $\frac{\partial K_1}{\partial x}(0,y) > a > 0$ for any $y \in [g_X(1),1]$ we deduce the existence of a natural number m such that $n_2(K(x,y),X) = n_2(x,y,X)+i$, $-m \leq i \leq m$ for small x. From $\pi_2\ H\ h_1(x,y,X) = g_X^{n_1(x,y,X)+k}(y)$, $k \geq 0$ and lemma 5 we have $\pi_2 h_2(K(x,y),X) = g_X^{n_2(K(x,y),X)}(y) < \pi_2\ H\ h_1(x,y,X)$ for x small enough. Then

Lemma 6: Under the hypotesis above, γ and the canonical component of $X|_{T^2}$ containing p are contained in $\Omega(X)$.

Lemma 7: Under the same hypotesis, $\gamma \subset \overline{\mathrm{Per}\ X}$

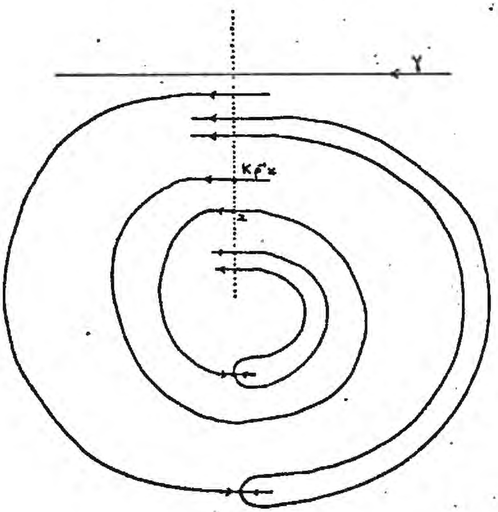
Proof: For $\rho(x,y) = \pi_1 h_2^{-1} Hh_1(x,y)$ and x_1, x_2 small enough with $\pi_2 h_1(x_1,y) = \pi_2 h_1(x_2,y)$ we have

$$\left| \frac{\rho(x_1,y) - \rho(x_2,y)}{x_1 - x_2} \right| \geq M \left(\frac{\lambda_1}{\lambda_2}\right)^{n_1(x_1,y)}, \quad M>0 \text{ constant}$$

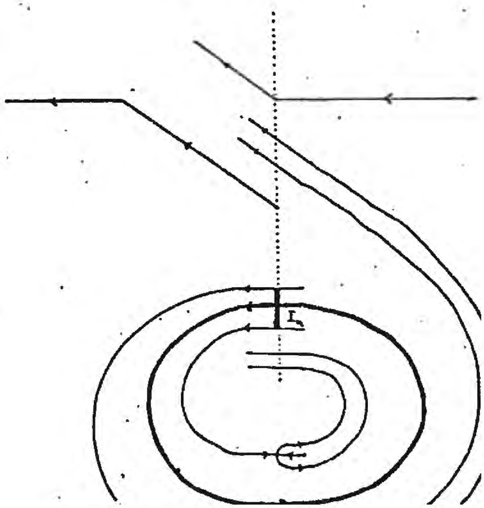
and then,

$$|K\rho^{-1}(x_1,y) - K\rho^{-1}(x_2,y)| \leq c|x_1 - x_2|, \quad 0<c<1$$

Thus, for $y_n \to y$ we deduce the existence of intervals I_n where $K\rho^{-1}$ is a contraction, hence, the existence of a hyperbolic fixed point in I_n



F_γ



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