

A splitting theorem for affine skew-product flows

Fritz Colonius, Alexandre J. Santana

Angaben zur Veröffentlichung / Publication details:

Colonius, Fritz, and Alexandre J. Santana. 2016. "A splitting theorem for affine skew-product flows." *Mathematische Nachrichten* 289 (16): 1995–2006.
<https://doi.org/10.1002/mana.201500160>.

Nutzungsbedingungen / Terms of use:

licgercopyright

Dieses Dokument wird unter folgenden Bedingungen zur Verfügung gestellt: / This document is made available under these conditions:

Deutsches Urheberrecht

Weitere Informationen finden Sie unter: / For more information see:

<https://www.uni-augsburg.de/de/organisation/bibliothek/publizieren-zitieren-archivieren/publiz/>



A splitting theorem for affine skew-product flows

Fritz Colonius^{*1} and Alexandre J. Santana^{**2}

¹ Institut für Mathematik, Universität Augsburg, Universitätsstr. 14, 86159, Augsburg, Germany

² Departamento de Matemática, Universidade Estadual de Maringá, Av. Colombo, 5.790, 87020-900, Maringá, Brazil

Key words Topological conjugacy, skew product flows, Lind's functional equation, fiber entropy

MSC (2010) 37B05, 37B55, 93B99, 22F05

Topological conjugacy for continuous skew product flows on topological group bundles and semidirect products is studied resulting in a splitting theorem. The results are used to discuss fiber entropy.

1 Introduction

This paper discusses topological conjugacy for skew product flows on topological group bundles and semidirect products. On one hand, our results are generalizations of contributions to topological conjugacy of linear and affine skew product flows, which were mainly motivated by bilinear control systems; see Ayala, Colonius and Kliemann [2] and Colonius and Santana [5], as well as Kawan, Rocio and Santana [7] for flows on Lie groups. On the other hand, there are close analogies to classical (and much more general) results by Lind [9] in the framework of ergodic skew product systems and splitting theorems. Our results may be viewed as topological versions of some of Lind's results.

The contents of this paper is as follows: In Section 2 some basic properties of topological groups and semidirect products are collected. Section 3 discusses flows on semidirect products, in particular, of Lie groups and topological conjugacy on these groups. Section 4 generalizes the discussion of topological conjugacies to skew product flows on topological group bundles. Theorem 4.8 shows that topological skew conjugacy is equivalent to solvability of a certain functional equation. It is shown that conjugacy results for linear and affine skew product which are valid for hyperbolic systems are a special case. Furthermore the relation to Lind's [9] functional equation and his splitting theorem for measurable conjugacy is explained. Finally, Section 5 presents an application to skew-product transformation semigroups and fiber entropy.

2 Preliminaries

In this section we recall some notation (see, e.g., Kechris [8], Appendix I) and facts on automorphisms of topological groups.

Let H and G be topological groups and in order to avoid confusion denote by $*$ the product in G . Consider the following continuous action given by homeomorphisms:

$$\xi : H \times G \longrightarrow G \quad \text{such that} \quad \xi(a, b) = ab.$$

Suppose that for all $h_1, h_2 \in H$ and $g \in G$

$$e_H g = g, (h_1 h_2) g = h_1(h_2 g), \tag{2.1}$$

* Corresponding author: e-mail: fritz.colonius@math.uni-augsburg.de, Phone: +49 821 598 2246, Fax: +49 821 598 2193

** e-mail: ajsantana@uem.br, Phone: +55 44 30114504 Fax: +55 44 30113873

and for all $h \in H$ and $g_1, g_2 \in G$

$$he_G = e_G, h(g_1 * g_2) = hg_1 * hg_2, \quad (2.2)$$

where e_H and e_G are the neutral elements of H and G , respectively. A simple consequence is that for all $h \in H, g \in G$

$$hg * h(g^{-1}) = h(g * (g^{-1})) = he_G = e_G, \text{ hence } h(g^{-1}) = (hg)^{-1}. \quad (2.3)$$

Furthermore each h induces an automorphism in G (i.e., an invertible topological group homomorphism) defined by $g \mapsto \xi(h, g)$. The homomorphism property is (2.2) and invertibility follows using (2.1). Associated with this automorphism we have the homomorphism

$$\varsigma : H \longrightarrow \text{Aut } G \text{ given by } \varsigma(h)(g) := \xi(h, g) \text{ for all } g \in G.$$

Each pair $(h, g) \in H \times G$ defines two maps in G ,

$$f \mapsto g * \varsigma(h)(f) = g * \xi(h, f) \text{ and } f \mapsto \varsigma(h)(f) * g = \xi(h, f) * g.$$

Thus we obtain two group structures for $H \times G$, called left semi-direct product and right semi-direct product, defined by the homomorphism ς :

$$(h_1, g_1)(h_2, g_2) = (h_1 h_2, g_1 * \varsigma(h_1)(g_2)) = (h_1 h_2, g_1 * \xi(h_1, g_2)) = (h_1 h_2, g_1 * h_1 g_2)$$

and

$$(h_1, g_1)(h_2, g_2) = (h_1 h_2, \varsigma(h_1)(g_2) * g_1) = (h_1 h_2, \xi(h_1, g_2) * g_1) = (h_1 h_2, h_1 g_2 * g_1).$$

In general, we can begin the construction of semi-direct product with any homomorphism ς and this map gives rise to the action $(h, g) \mapsto \varsigma(h)(g)$, but continuity of ς does not imply continuity of ξ that must be axiomatized (as done above). Here we consider in $H \times G$ the right semi-direct product (and just call it semi-direct product), which is continuous, and denote this group by $H \rtimes G$. Note that the neutral element is (e_H, e_G) and the inverse is given by $(h, g)^{-1} = (h^{-1}, h^{-1}g^{-1})$.

Clearly, $H \rtimes G$ again is a topological group and there is a natural continuous action of $H \rtimes G$ on G given by

$$(h, g_1) \cdot g_2 = hg_2 * g_1 \text{ for } h \in H, g_1, g_2 \in G. \quad (2.4)$$

An affine automorphism of G is any map σ of the form $\sigma(g) = \varsigma(g) * h$, where h is a fixed element of G and ς is an automorphism of G . Any such σ can be identified with the pair (ς, h) , ς being the automorphic part of σ and $h = \sigma(e_G)$, the translation part. If $\sigma_1 = (\varsigma_1, h_1)$, $\sigma_2 = (\varsigma_2, h_2)$ are affine automorphisms, then $\sigma_1 \sigma_2 = (\varsigma_1 \varsigma_2, \varsigma_1(h_1) * h_2)$, thus the group of affine automorphisms of G can be identified with the semidirect product of the automorphism group of G with G , where the automorphism group of G acts by evaluation on G . If now H acts by automorphisms on G , then $H \rtimes G$ acts by affine automorphisms on G given by the above equality (2.4). If H acts on G faithfully (i.e., if $hg = g$ for all g , then $h = e_H$), then H can be viewed as a group of automorphisms of G . In this case also $H \rtimes G$ acts faithfully on G , hence $H \rtimes G$ can be viewed as a group of affine automorphisms of G .

If H and G are Lie groups, the Lie algebra of $H \rtimes G$ is denoted by $\mathfrak{h} \rtimes \mathfrak{g}$, where \mathfrak{h} is the Lie algebra of H and \mathfrak{g} is the Lie algebra of G . Note that for simplicity we use the same product symbol for the group and algebra. As usual $\exp_{H \rtimes G} : \mathfrak{h} \rtimes \mathfrak{g} \rightarrow H \rtimes G$ denotes the known exponential map.

3 Flows on semidirect products of Lie groups

In this section we discuss topological conjugacy of flows on semidirect products of Lie groups.

Recall the following concepts. Let M be a smooth manifold and $\mathfrak{X}(M)$ be the space of smooth vector fields on M . Let $X_1, X_2 \in \mathfrak{X}(M)$ be complete vector fields and Φ_1 and Φ_2 their associated flows (or dynamical systems). The flows Φ_1 and Φ_2 , and the vector fields X_1, X_2 , are called topologically conjugate if there exists a homeomorphism $h : M \rightarrow M$ such that $h(\Phi_1(t, x)) = \Phi_2(t, h(x))$ for all $x \in M$ and $t \in \mathbb{R}$, and h is called a topological conjugacy.

As in the classical case of linear autonomous differential equations here the existence of homeomorphic fundamental domains is essential. We define a type of fundamental domain in a general context: Consider a topological space M and a flow $\Phi : \mathbb{R} \times M \rightarrow M$. A *fundamental domain* of Φ is a pair (Z, τ) where Z is a subset of M and $\tau : M \rightarrow \mathbb{R}$ is a continuous map such that for all $x \in M$ it holds that $\Phi(t, x) \in Z$ if and only if $t = \tau(x)$.

Let $\pi : H \rtimes G \rightarrow H$ be the canonical projection onto the Lie group H . If $\Upsilon_t(h, g) = \exp_{H \rtimes G}(tX)(h, g)$ is a flow on $H \rtimes G$, where $X = (A, B) \in \mathfrak{h} \rtimes \mathfrak{g}$ and $(h, g) \in H \rtimes G$, we denote by Ω the flow on H given by

$$\Omega_t(h) = \exp_H(tA)h \quad \text{with } h \in H. \quad (3.1)$$

The next result from Moskowitz and Sacksteder [10, Theorem 3.1] describes the flow on $H \rtimes G$. In this theorem, the exponential map $\exp_{H \rtimes G}$ for a semidirect product $H \rtimes G$ of arbitrary connected Lie groups H and G is given by

$$\exp_{H \rtimes G}(h, g) = (\exp_H(h), \mathcal{E}_G^D(g)),$$

where \mathcal{E}_G^D is defined as follows. Let $g(t)$ be the solution of

$$g'(t) = dL_{g(t)}\gamma(t) \quad (3.2)$$

with $g(0) = e_G$, $\gamma(t) = \exp(tD)\gamma_0$ and $\gamma : \mathbb{R} \rightarrow \mathfrak{g}$. Define

$$\mathcal{E}_G^D : \mathfrak{g} \longrightarrow G, \quad \mathcal{E}_G^D(\gamma_0) := g(1),$$

where h is identified with $(h, 0)$ and hence induces a derivation $D = \text{ad}_h$ on the Lie algebra of G .

Lemma 3.1 For $X = (A, B) \in \mathfrak{h} \rtimes \mathfrak{g}$, the flow $\Upsilon_t(h, g) = \exp_{H \rtimes G}(tX) \cdot (h, g)$ on $H \rtimes G$ is given by

$$\exp_{H \rtimes G}(tX) \cdot (h, g) = (\exp_H(tA)h, \mathcal{E}_G^D(tB)).$$

Let M and P be topological spaces and $\pi : M \times P \rightarrow M$ be the canonical projection, then we have the following result proved in Kawan, Rocio and Santana [7, Corollary 4].

Lemma 3.2 Let M and P be topological spaces and $\pi : M \times P \rightarrow M$ be the canonical projection. Assume that $\tilde{\Lambda}^1$ and $\tilde{\Lambda}^2$ are flows on M , and Λ^1 and Λ^2 are flows on $M \times P$ such that the diagram

$$\begin{array}{ccc} M \times P & \xrightarrow{\Lambda_t^i} & M \times P \\ \pi \downarrow & & \downarrow \pi \\ M & \xrightarrow{\tilde{\Lambda}_t^i} & M \end{array}$$

commutes for every $t \in \mathbb{R}$. Suppose that there exist fundamental domains $(\tilde{W}^i, \tilde{\tau}^i)$ for the flows $\tilde{\Lambda}^i$ such that \tilde{W}^1 is homeomorphic to \tilde{W}^2 . Then Λ^1 is topologically conjugate to Λ^2 .

The rest of this section is an adaptation of [7, Proposition 12 and Remark 13].

Proposition 3.3 Consider the affine group $H \rtimes G$ for Lie groups G and H . Let $\pi : H \rtimes G \rightarrow H$ be the canonical projection. Take flows $\Upsilon_t^i(h, g) = \exp_{H \rtimes G}(tX_i)(h, g)$, $i = 1, 2$, on $H \rtimes G$ and suppose that there exist homeomorphic fundamental domains for the flows Ω_t^i on H as in (3.1). Then Υ^1 is topologically conjugate to Υ^2 .

Proof. Let $X_i = (A_i, B_i) \in \mathfrak{h} \rtimes \mathfrak{g}$ for $i = 1, 2$. By Lemma 3.1, we have that for every $t \in \mathbb{R}$

$$\pi(\Upsilon_t^i(h, g)) = \pi(\exp_{H \rtimes G}(t(A_i, B_i))(h, g)) = \exp_H(tA_i)h = \Omega_t^i(h) = \Omega_t^i(\pi(h, g)).$$

That is, the following diagram commutes:

$$\begin{array}{ccc} H \rtimes G & \xrightarrow{\Upsilon_t^i(\cdot)} & H \rtimes G \\ \pi \downarrow & & \downarrow \pi \\ H & \xrightarrow{\Omega_t^i(\cdot)} & H \end{array}$$

Then the proposition follows from Lemma 3.2. \square

As a consequence we obtain the following corollary.

Corollary 3.4 *If H is a nilpotent or abelian group, then any two flows on $H \rtimes G$ are topologically conjugate.*

Proof. In fact, using the same notation as above, take flows $\Upsilon_t^i(h, g) = \exp(tX_i)(h, g)$, $i = 1, 2$, on $H \rtimes G$. Then $\Omega_t^i(h) = \exp_H(tA_i)h$ with $h \in H$ are flows on H . Hence, by Section 3 in [7] there exist fundamental domains for Ω^i , $i = 1, 2$. Therefore, by Proposition 3.3 it follows that Υ^1 is topologically conjugate to Υ^2 , if H is nilpotent or abelian. \square

Another consequence is the following result for a semisimple Lie group H . Consider the Iwasawa decomposition $H = ANK = NAK$. Take $X_i = (A_i, B_i) \in \mathfrak{h} \rtimes \mathfrak{g}$, but with $A_i \in \mathfrak{a}$ for $i = 1, 2$ or $A_i \in \mathfrak{n}$ for $i = 1, 2$, where \mathfrak{a} and \mathfrak{n} are the Lie algebras of A and N , respectively. Then again by Section 3 in [7] the flows on H , $\Omega_t^1(h) = \exp_H(tA_1)h$ and $\Omega_t^2(h) = \exp_H(tA_2)h$ are topologically conjugate. Hence, by the last proposition it follows that these flows on $H \rtimes G$ are topologically conjugate.

4 Skew product flows and semidirect products

In this section we generalize our discussion of topological conjugacy to skew product flows on topological group bundles.

Consider with $\mathbb{T} = \mathbb{R}$ or \mathbb{Z} a continuous dynamical system $\vartheta_t : B \rightarrow B$, $t \in \mathbb{T}$, on a base space B , which is a metric space, and consider the topological group bundle $H \times B$. Then let $\Phi : \mathbb{T} \times H \times B \rightarrow H \times B$ be a continuous map of the form

$$\Phi_t(h, b) := (\phi_t(h, b), \vartheta_t b), \quad (4.1)$$

where the first component satisfies for all $s, t \in \mathbb{T}$ and $b \in B$, $h \in H$

$$\phi_0(h, b) = h, \phi_{t+s}(h, b) = \phi_t(e_H, \vartheta_s b) \phi_s(h, b). \quad (4.2)$$

Then one finds for $s = 0$

$$\phi_t(h, b) = \phi_t(e_H, b) \phi_0(h, b) = \phi_t(e_H, b)h,$$

and hence ϕ satisfies the cocycle property

$$\phi_{t+s}(h, b) = \phi_t(e_H, \vartheta_s b) \phi_s(h, b) = \phi_t(\phi_s(h, b), \vartheta_s b) \quad \text{for all } t, s \in \mathbb{R}.$$

Thus Φ is a skew product system, and hence this construction provides us with a class of continuous skew product systems on $H \times B$, where by (4.2) the associated cocycle ϕ_t is compatible with the group structure on H .

Remark 4.1 Here and in the following we consider group bundles which are topologically trivial. The results are also valid, when B is a compact metric space and the considered group bundle is only locally trivial.

Now we will construct “affine” skew product systems Ψ on $(H \rtimes G) \times B$ which are compatible with the group structures and with the natural actions of H on G and of $H \rtimes G$ on G .

Definition 4.2 A skewing function $a : \mathbb{T} \times B \rightarrow G$ is a continuous map satisfying $a(0, b) = e_G$ and

$$a(t + s, b) = \phi_t(e_H, \vartheta_s b) a(s, b) * a(t, \vartheta_s b) = (\phi_t(e_H, \vartheta_s b), a(t, \vartheta_s b)) \cdot a(s, b). \quad (4.3)$$

We think of a as an inhomogeneous term. We use it to define a skew product system Ψ on $(H \rtimes G) \times B$. Consider, for $t \in \mathbb{T}$, the map Ψ_t defined by

$$\Psi_t : (H \rtimes G) \times B \longrightarrow (H \rtimes G) \times B, \quad \Psi_t(h, g, b) := (\psi_t(h, g, b), \vartheta_t b)$$

with $\psi_t : (H \rtimes G) \times B \rightarrow H \rtimes G$ given by

$$\psi_t(h, g, b) := (\phi_t(h, b), \phi_t(e_H, b)g * a_t(b)) = (\phi_t(h, b), (\phi_t(e_H, b), a_t(b)) \cdot g) \quad (4.4)$$

and ϕ_t given in (4.1) and (4.2). Since $a : \mathbb{T} \times B \rightarrow G$ is continuous, also $\psi : \mathbb{T} \times (H \rtimes G) \times B \rightarrow H \rtimes G$ and $\Psi : \mathbb{T} \times (H \rtimes G) \times B \rightarrow (H \rtimes G) \times B$ are continuous. By condition (4.3) the dynamical system property for Ψ or, equivalently, the cocycle property for the first component,

$$\psi_{t+s}(h, g, b) = \psi_t(\psi_s(h, g, b), \vartheta_s b) \in H \rtimes G$$

holds: The left hand side is

$$\psi_{t+s}(h, g, b) = (\phi_{t+s}(h, b), \phi_{t+s}(e_H, b)g * a_{t+s}(b)) \quad (4.5)$$

and the right hand side is

$$\begin{aligned} & \psi_t(\psi_s(h, g, b), \vartheta_s b) \\ &= \psi_t((\phi_s(h, b), \phi_s(e_H, b)g * a_s(b)), \vartheta_s b) \\ &= (\phi_t(\phi_s(h, b), \vartheta_s b), \phi_t(e_H, \vartheta_s b) [\phi_s(e_H, b)g * a_s(b)] * a_t(\vartheta_s b)). \end{aligned} \quad (4.6)$$

The first components of (4.5) and (4.6) (i.e., the components in G) coincide. For the second component (in H) we use the distributive law (2.2), the cocycle property of ϕ and the defining property (4.3) of a . It follows that

$$\begin{aligned} & \phi_t(e_H, \vartheta_s b) [\phi_s(e_H, b)g * a_s(b)] * a_t(\vartheta_s b) \\ &= \phi_t(e_H, \vartheta_s b) \phi_s(e_H, b)g * \phi_t(e_H, \vartheta_s b) a_s(b) * a_t(\vartheta_s b) \\ &= \phi_{t+s}(e_H, b)g * a_{t+s}(b). \end{aligned} \quad (4.7)$$

Thus Ψ_t is given by the skew product flow Φ on $G \times B$ (with base flow ϑ on B and cocycle ϕ) and the associated skewing map (the affine term)

$$a : \mathbb{R} \times B \longrightarrow G : (t, b) \longmapsto a_t(b)$$

satisfying (4.3).

We illustrate the constructions above by discussing the relations to linear and affine flows. A linear skew product flow $\Phi_t(h, b) = (\phi_t(h, b), \vartheta_t b)$ on the group bundle $\text{Gl}(d, \mathbb{R}) \times B \rightarrow B$ with $H = \text{Gl}(d, \mathbb{R})$ is defined as follows. Here the product of $\text{Gl}(d, \mathbb{R})$ is the matrix multiplication, $e_H = I$ and for $b \in B$, $h \in \text{Gl}(d, \mathbb{R})$ one has $\phi_t(e_H, b) = \phi_t(e_H, b)h = \phi_t(I, b)h$ and

$$\phi_0(h, b) = h \quad \text{and} \quad \phi_{t+s}(h, b) = \phi_t(I, \vartheta_s b) \phi_s(h, b), \quad (4.8)$$

hence

$$\begin{aligned} \Phi_{t+s}(h, b) &= (\phi_{t+s}(h, b), \vartheta_{t+s} b) = (\phi_t(I, \vartheta_s b) \phi_s(h, b), \vartheta_t \vartheta_s b) \\ &= \Phi_t(\phi_s(h, b), \vartheta_s b) = \Phi_t(\Phi_s(h, b)). \end{aligned}$$

More specifically, this flow may be generated by a homogeneous bilinear control system in $\text{Gl}(d, \mathbb{R})$ of the form

$$\dot{X} = \left[A_0 + \sum_{i=1}^m u_i(t) A_i \right] X, \quad u \in \mathcal{U}; \quad (4.9)$$

here the controls $u = (u_i)$ are taken in

$$\mathcal{U} := \{u \in L^\infty(\mathbb{R}, \mathbb{R}^m) \mid u(t) \in U \text{ for almost all } t \in \mathbb{R}\},$$

where U is a compact convex subset of \mathbb{R}^m . Then $B = \mathcal{U}$ is a metrizable weak* compact set and the shift $\vartheta : \mathbb{Z} \times \mathcal{U} \times \mathcal{U}, (t, u) \mapsto u(t + \cdot)$ is continuous. Let $X_u(t)$ be the solution of the ordinary differential equation in (4.9) with initial condition $X_u(0) = I$. Then one has for $(h, u) \in \text{Gl}(d, \mathbb{R}) \times \mathcal{U}$

$$\phi_t(h, u) = X_u(t)h = \phi_t(I, u)h. \quad (4.10)$$

Then the corresponding skew product flow $\Phi = (\vartheta, \phi)$ on $\mathcal{U} \times \text{Gl}(d, \mathbb{R})$ is continuous (see, e.g., Colonius and Kliemann [3, Theorem 9.5.5]).

We note that homogeneous bilinear control systems of special type induce linear skew product flows for other Lie groups, e.g., on $\mathcal{U} \times \text{Sl}(d, \mathbb{R})$.

Remark 4.3 It is well known, that the homogeneous bilinear control system (4.9) also induces a semigroup in the Lie group $\text{Gl}(d, \mathbb{R})$. This is an entirely different construction.

For linear flows one takes G as the additive group \mathbb{R}^d (thus $*$ means $+$) and defines a skewing map a by

$$a_t(b) = \int_0^t \Phi_{t-\tau}(f(b, \tau), \theta_\tau b) d\tau = \int_0^t \varphi_{t-\tau}(f(b, \tau), \theta_\tau b) d\tau,$$

where integration is only performed in \mathbb{R}^d (see Colonius and Santana [5, Definition 2.1 and Remark1]) and

$$f(b, t+s) = f(\theta_s(b), t) \quad \text{for all } b \in B \text{ and almost all } t, s \in \mathbb{R}.$$

Here $e_H = I_d \in \text{Gl}(d, \mathbb{R})$ and $a(t, b)$ satisfies (4.3) (cf. [5, Proposition 1]), hence it is indeed a skewing function:

$$\begin{aligned} a_{t+s}(b) &= \int_0^{t+s} \varphi_{t+s-\tau}(f(b, \tau), \theta_\tau b) d\tau \\ &= \int_0^s \varphi_{t+s-\tau}(f(b, \tau), \theta_\tau b) d\tau + \int_s^{t+s} \varphi_{t+s-\tau}(f(b, \tau), \theta_\tau b) d\tau \\ &= \int_0^s \phi_t(I, \vartheta_{s-\tau+\tau} b) \phi_{s-\tau}(f(b, \tau), \theta_\tau b) d\tau + \int_0^t \varphi_{t-\tau}(f(b, \tau+s), \theta_{\tau+s} b) d\tau \\ &= \phi_t(I, \vartheta_s b) \int_0^s \phi_{s-\tau}(f(b, \tau), \theta_\tau b) d\tau + \int_0^t \varphi_{t-\tau}(f(b, \tau+s), \theta_{\tau+s} b) d\tau \\ &= \phi_t(I, \vartheta_s b) \int_0^s \Phi_{t-\tau}(\theta_\tau b, f(b, \tau)) d\tau + \int_0^t \varphi_{t-\tau}(f(\theta_s b, \tau), \theta_\tau \theta_s b) d\tau \\ &= \phi_t(e_H, \vartheta_s b) a_s(b) * a_t(\vartheta_s b). \end{aligned}$$

Returning to the general situation, the beautiful thing is that each of the skew product systems Φ on $H \times B$ and Ψ on $(H \times G) \times B$ induces a skew product system on $G \times B$. They are defined in the following way, beginning with the “linear” flow Φ .

Definition 4.4 Define the following skew product flow $\tilde{\Phi}_t$ in $G \times B$

$$\tilde{\Phi}_t : G \times B \longrightarrow G \times B, \quad \tilde{\Phi}_t(g, b) = (\tilde{\phi}_t(g, b), \vartheta_t b)$$

with

$$\tilde{\phi}_t : G \times B \longrightarrow G, \quad \tilde{\phi}_t(g, b) = \phi_t(e_H, b)g.$$

This is a system of the form (4.4), where we take the trivial affine term $a(b) = e_G, b \in B$, and omit the first component in H . Now we show that the first component of $\tilde{\Phi}_t$ is in fact a cocycle.

$$\tilde{\phi}_{t+s}(g, b) = \phi_{t+s}(e_H, b)g = [\phi_t(e_H, \vartheta_s b) \phi_s(e_H, b)]g.$$

On the other hand, using the associative law (2.1),

$$\begin{aligned}\tilde{\phi}_t(\tilde{\phi}_s(g, b), \vartheta_s b) &= \phi_t(e_H, \vartheta_s b) \tilde{\phi}_s(g, b) = \phi_t(e_H, \vartheta_s b) [\phi_t(e_H, b)g] \\ &= [\phi_t(e_H, \vartheta_s b) \phi_s(e_H, b)] g.\end{aligned}$$

Hence $\tilde{\Phi}$ is a skew product flow.

Also for the affine system Ψ there is an induced skew product system in $G \times B$.

Definition 4.5 Define the following skew product system $\tilde{\Psi}_t, t \in \mathbb{T}$, in $G \times B$

$$\tilde{\Psi}_t : G \times B \longrightarrow G \times B, \quad \tilde{\Psi}_t(g, b) := (\tilde{\psi}_t(g, b), \vartheta_t b)$$

given by

$$\tilde{\psi}_t(g, b) = \phi_t(e_H, b)g * a_t(b) = (\phi_t(e_H, b), a_t(b)) \cdot g.$$

So this is just the G -component of ψ from (4.4) and a cocycle by equality (4.8).

In the remainder of this section we will be concerned with topological conjugations of the defined flows. We begin with the definition of topological conjugation of skew products flows.

Definition 4.6 Let $\Gamma^1 = (\gamma^1, \vartheta^1)$ and $\Gamma^2 = (\gamma^2, \vartheta^2)$ be skew product flows on topological group bundles $H^1 \times B^1$ and $H^2 \times B^2$, respectively. We say that Γ^1 and Γ^2 are topologically skew conjugate, or just topologically conjugate, if there exists a skew homeomorphism

$$(h_H, h_B) : H^1 \times B^1 \longrightarrow H^2 \times B^2$$

such that $(h_H, h_B)(\Gamma_t^1(x, b)) = \Gamma_t^2((h_H, h_B)(x, b))$; i.e., $h_B : B^1 \rightarrow B^2, h_H : H^1 \times B^1 \rightarrow H^2$ are maps with

$$h_B(\vartheta_t^1 b) = \vartheta_t^2(h_B(b)) \quad \text{for all } t \in \mathbb{T} \text{ and } b \in B^1, \quad (4.11)$$

$$h_H(\gamma^1(t, x, b), \vartheta_t^1 b) = \gamma^2(t, h_H(x, b), h_B(b)) \quad \text{for all } t \in \mathbb{T}, b \in B^1, \text{ and } x \in H^1. \quad (4.12)$$

Thus topological skew conjugacy requires that the base flows are topologically conjugate via the homeomorphism h_B and (4.12) holds.

Our first result, concerned with topological conjugations of these flows, is a consequence of Lemma 3.2.

Proposition 4.7 Consider flows Φ^i on $H \times B$ and Ψ^i on $G \times B$ with $i = 1, 2$, as defined above. Assume that there exist homeomorphic fundamental domains for the flows Φ^1 and Φ^2 . Then Ψ^1 is topologically conjugate to Ψ^2 .

Proof. Consider the following diagram

$$\begin{array}{ccc}(H \rtimes G) \times B & \xrightarrow{\Psi_t^i} & (H \rtimes G) \times B \\ \pi \downarrow & & \downarrow \pi \\ H \times B & \xrightarrow{\Phi_t^i} & H \times B\end{array}$$

where $\pi : (H \rtimes G) \times B \rightarrow H \times B$ is defined as $\pi(h, g, b) = (h, b)$. Noting that

$$\begin{aligned}\pi(\Psi_t^i(h, g, b)) &= \pi(\phi_t^i(h, b), \phi_t^i(e_H, b)g * a_t(b), \vartheta_t b) \\ &= (\phi_t^i(h, b), \vartheta_t b) = \Phi_t^i(\pi(h, g, b)),\end{aligned}$$

one sees that the diagram above commutes. Hence by Lemma 3.2 the proposition is proved. \square

Next we will give conditions implying that the induced flows $\tilde{\Psi}_t$ and $\tilde{\Phi}_t$ are topologically conjugate. So we need to find

$$(h_G, h_B) : G \times B \longrightarrow G \times B,$$

conjugating $\tilde{\Psi}_t$ and $\tilde{\Phi}_t$ with $h_B = id_B$. Clearly, in this case, the only difficulty lies in the construction of $h_G : G \times B \rightarrow G$ which must satisfy

$$h_G(\tilde{\Psi}_t(g, b), \vartheta_t b) = \tilde{\Phi}_t(h_G(g, b), b). \quad (4.13)$$

Theorem 4.8 *The flows $\tilde{\Psi}_t$ and $\tilde{\Phi}_t$ are conjugate if and only if there is a continuous map $b \mapsto e(b) : B \rightarrow G$ solving the functional equation*

$$e(\vartheta_t b) = \phi_t(e_H, b)e(b) * a_t(b) = (\phi_t(e_H, b), a_t(b)) \cdot e(b). \quad (4.14)$$

Proof. Suppose that Equation (4.14) has a continuous solution $e(\cdot)$. It follows that (note that G is not necessarily Abelian)

$$(e(\vartheta_t b))^{-1} = (a_t(b))^{-1} * (\phi_t(e_H, b)e(b))^{-1}. \quad (4.15)$$

Define a map $h_G : G \times B \rightarrow G$ as $h_G(g, b) := g * (e(b))^{-1}$. Then, using (2.3), one computes

$$\begin{aligned} h_G(\tilde{\Psi}_t(g, b), \vartheta_t b) &= h_G(\phi_t(e_H, b)g * a_t(b), \vartheta_t b) \\ &= \phi_t(e_H, b)g * a_t(b) * (e(\vartheta_t b))^{-1} \\ &= \phi_t(e_H, b)g * a_t(b) * (a_t(b))^{-1} * (\phi_t(e_H, b)e(b))^{-1} \\ &= \phi_t(e_H, b)g * (\phi_t(e_H, b)e(b))^{-1} \\ &= \phi_t(e_H, b)g * \phi_t(e_H, b)(e(b))^{-1} \\ &= \phi_t(e_H, b)(g * (e(b))^{-1}) \\ &= \tilde{\Phi}_t(g * (e(b))^{-1}, b) \\ &= \tilde{\Phi}_t(h_G(g, b), b). \end{aligned}$$

Therefore $\tilde{\Psi}_t$ is conjugate to $\tilde{\Phi}_t$. By continuity of $b \mapsto e(b)$ the map h_G is continuous. The continuous inverse of (h_G, id_B) is $(h_G, id_B)^{-1}(g, b) = (g * e(b), b)$, thus this is a homeomorphism.

Conversely, suppose that $\tilde{\Phi}_t$ and $\tilde{\Psi}_t$ are topologically conjugate with $h_B = id_B$ and $h_G : G \times B \rightarrow G$. Then h_G satisfies (4.13) and hence for all $b \in B, g \in G, t \in \mathbb{T}$

$$\begin{aligned} h_G(\phi_t(e_H, b)g * a_t(b), \vartheta_t b) &= h_G(\tilde{\Psi}_t(g, b), \vartheta_t b) = \tilde{\Phi}_t(h_G(g, b), b) \\ &= \phi_t(e_H, b)h_G(g, b). \end{aligned}$$

Clearly, $e : B \rightarrow G, e(b) := h_G(b, g)g^{-1}$ is continuous. Then the same computation as above shows that e is a solution of the functional equation (4.15) which is equivalent to (4.14). \square

In the case of linear flows (4.8) additional assumptions are necessary in order to ensure topological conjugacy of $\tilde{\Phi}_t$ and $\tilde{\Psi}_t$.

Remark 4.9 (Linear flows) The conditions above on $e(b) \in G$ coincide with $e(b, 0) \in \mathbb{R}^d$ in the case of affine-linear flows on vector bundles, cf. [5, Theorem 2.5, in particular, assumption (iii)] (observe that here $I_d \in \text{Gl}(d, \mathbb{R}) = H$ is the neutral element e_H): In the proof of [5, Lemma 2.3] it is shown that

$$e(b, t) = \int_0^t \varphi(t-s, \theta_s b, f(b, s)) ds + \varphi(t, b, x).$$

(again, $*$ means $+$). Note that $x = e(b, 0)$ and $a(t, b) = \int_0^t \varphi(t-s, \theta_s b, f(b, s)) ds$ and $e_H = I \in H = \text{Gl}(d, \mathbb{R})$. Now by (4.10) $\phi_t(h, u) = X_u(t)h$, and hence

$$\phi_t(e_H, b)e(b) = X_u(t)Ie(b, 0) = X_u(t)x = \varphi(t, b, x),$$

implying, as claimed,

$$e(b, t) = a(t, b) * \phi_t(e_H, b)e(b, 0).$$

Now note that conjugacy of the flows $\tilde{\Phi}_t$ and $\tilde{\Psi}_t$ also implies conjugacy results for affine flows: In fact, denote the topological conjugacy by \sim , consider two flows $\tilde{\Psi}_t^1$ and $\tilde{\Psi}_t^2$ of the form

$$\begin{aligned}\tilde{\Psi}_t^1(g, b) &:= (\tilde{\psi}_t^1(g, b), \vartheta_t b) = (\phi_t(h, b), \phi_t(e_H, b)g * a_t^1(b)), \\ \tilde{\Psi}_t^2(v, b) &:= (\tilde{\psi}_t^2(g, b), \vartheta_t b) = (\phi_t(h, b), \phi_t(e_H, b)g * a_t^2(b))\end{aligned}$$

and take the corresponding linear flows $\tilde{\Phi}_t^1$ and $\tilde{\Phi}_t^2$. For linear flows (4.8) on vector bundles, Ayala, Colonius and Kliemann [2, Corollary 3.4] shows that a hyperbolicity condition implies topological conjugacy of two linear flows (with topologically conjugate base flows). In this case $\tilde{\Phi}_t^1 \sim \tilde{\Phi}_t^2$. Now if the hypothesis of Theorem 4.8 is valid, it also follows that $\tilde{\Psi}_t^1 \sim \tilde{\Phi}_t^1$ and hence $\tilde{\Psi}_t^1 \sim \tilde{\Psi}_t^2$.

Next we discuss the relation of our constructions and Theorem 4.8 to the work of Lind [9] on a Splitting Theorem.

Lind considers the following situation. Let U be an invertible measure-preserving transformation acting on a Lebesgue measure space (X, μ) . Let G be a separable compact abelian group equipped with the Borel σ -algebra and Haar measure, and S be a (continuous, algebraic) automorphism of G . Let $\alpha : X \rightarrow G$ be measurable, called a skewing map. Since both S and translations preserve Haar measure, the map $U \times_\alpha S$ called the skew product of U with S on the Lebesgue space $X \times G$ defined by

$$(U \times_\alpha S)(x, g) := (Ux, Sg * \alpha(x))$$

is measurable and preserve the product of μ with Haar measure.

The skew product $U \times_\alpha S$ algebraically splits if there is an isomorphism W on $X \times G$ of the form $W(x, g) = (x, g * \beta(x))$, where $\beta : X \rightarrow G$ is measurable such that the conjugation relation

$$(U \times_\alpha S)W = W(U \times S)$$

holds. This conjugation relation is equivalent to the functional equation

$$\alpha(x) = \beta(Ux) * (S\beta(x))^{-1}. \quad (4.16)$$

Thus the algebraic splitting of $U \times_\alpha S$ is equivalent to solving this equation for a measurable function β , where α, U and S are given. Lind's main result ([9, p. 237]) shows that this is always possible.

Lind's Splitting Theorem. Equation (4.16) has a measurable solution β and hence skew products with ergodic automorphisms of compact abelian groups algebraically split.

The relation to our results is the following. In the discrete-time situation $\mathbb{T} = \mathbb{Z}$, one has

$$\vartheta_n = (\vartheta_1)^n \quad \text{for } n \in \mathbb{Z}.$$

Here $U := \vartheta_1$ is homeomorphism on B . Thus we replace the invertible measure preserving transformation U on the Lebesgue space X in Lind [9] by the homeomorphism ϑ_1 on the metric space B . Condition (4.3) for the affine term $a : \mathbb{Z} \times G$ takes the form: For every b one has $a_0(b) = e_G$ and

$$a_{n+m}(b) = \phi_n(e_H, \vartheta_m b) a_m(b) * a_n(\vartheta_m b) \quad \text{for all } n, m \in \mathbb{Z}.$$

and condition (4.4) has the form

$$\psi_n(h, g, b) := (\phi_n(h, b), \phi_n(e_H, b)g * a_n(b)) \quad \text{for } n \in \mathbb{Z}.$$

As observed at the end of Section 2, the element $\phi_1(e_H, b) \in H$ induces an automorphism ζ on G via $\zeta(g) = \phi_1(e_H, b)g, g \in G$. In Lind's framework [9], where $\vartheta_1 = U$, instead of $(H \ltimes G) \times B$ the space $B \ltimes G$ is considered and instead of $\phi_1(e_H, b)g, g \in G$, an automorphism S of the group $G = H$ is taken. If we also write $\alpha = a_1$ the formula

$$\phi_1(e_H, b) a_1(b) * a_1(\vartheta_1 b)$$

reduces to

$$S\alpha(b) * \alpha(Ub).$$

Here the flows $\tilde{\Phi}_t$ and $\tilde{\Psi}_t$ coincide with Φ and Ψ , respectively. Alluding to Lind's terminology, we consider the skew product of the flow ϑ on B with the (skew product flow) Φ on $B \times H$ with skewing function $\alpha : B \rightarrow G$. The result is the skew product system $\tilde{\Psi} = \Psi$ on $B \times G$.

In Theorem 4.8, we assume that Equation (4.14) has a continuous solution e , i.e., there is a continuous map $b \mapsto e(b) : B \rightarrow G$ with

$$e(\vartheta_t b) = \phi_t(e_H, b)e(b) * a_t(b) = (\phi_t(e_H, b), a_t(b)) \cdot e(b).$$

We get, with $t = 1$, $\vartheta_1 = U$, $a_1(b) = \alpha(b)$, and the automorphism S instead of $\zeta(g) = \phi_t(e_H, b)g$, $g \in G$, a map $e : B \rightarrow G = H$ satisfying

$$e(Ub) = Se(b) * \alpha(b).$$

Thus we look for a solution $\beta = e$ of Lind's functional equation

$$\alpha(b) = \beta(Ub) * (S\beta(b))^{-1}.$$

In the measure theoretic framework, the functional equation can always be solved by a measurable map β . Lind already noted that, in general, the topological analogue of his splitting theorem is not valid (cf. [9, p. 238]). In the topological framework additional assumptions are necessary, in order to get a solution (a continuous map β or $e : B \rightarrow G$) of Lind's functional equation. In the case of linear flows, a hyperbolicity assumption is needed, cf. Remark 4.9.

Remark 4.10 When we want to emphasize the dependence of $\tilde{\Psi}$ on the skewing function a we write it, in analogy to Lind's notation, as $\tilde{\Psi} = \vartheta \times_a \phi$. Thus Theorem 4.8 shows that the flow $\vartheta \times_a \phi$ is topologically conjugate to the flow $\vartheta \times \phi$, i.e., it splits algebraically and topologically.

Remark 4.11 The discussion of linear and affine flows shows that here a hyperbolicity assumption is required in order to obtain topological conjugacy of the flows $\tilde{\Phi}_t^1$ and $\tilde{\Psi}_t^1$. A similar result for more general skew product flows would require the development of corresponding spectral theory and hyperbolicity. Of special interest would be the case of principal fibre bundles.

5 Skew-product transformation semigroups and fiber entropy

Let S and T be topological semigroups acting on a topological spaces X and on a topological group H respectively. Suppose that S contains the identity e_S , represent the actions by $\sigma_1 : S \times X \rightarrow X$ and $\sigma_2 : T \times H \rightarrow H$ with $\sigma_1(s, x) = sx$ and $\sigma_2(t, h) = th$ and assume that both actions are surjective. Now we recall the definition of skew-product transformation semigroups given in Souza [11]. This notion is classical and there are several directions of research, for example in control theory the study of control flows (see e.g. [4]) and in topological dynamics the study of dynamics of group actions (see e.g. [6]).

In the context of the beginning of the previous section, the skew product transformation semigroup on the product space $H \times X$ is given by

$$\Phi : S \times H \times X \longrightarrow H \times X \quad \text{with} \quad \Phi(s, h, x) = (\phi(s, x)h, sx), \quad (5.1)$$

where $\phi : S \times X \rightarrow T$ is a cocycle, i.e., it is continuous and satisfies

$$\phi_{e_S}(x)h = h \text{ and } \phi_{s_1 s_2}(x) = \phi_{s_1}(s_2 x) \phi_{s_2}(x) \quad \text{for all } s_1, s_2 \in S, x \in X.$$

We can also write

$$\phi : S \times H \times X \longrightarrow T \quad \text{with} \quad \phi_s(h, x) = \phi_s(x)h.$$

Next define the following subsemigroup of T :

$$S = \{\phi_{s_n}(x_n) \phi_{s_{n-1}}(x_{n-1}) \dots \phi_{s_0}(x_0) : s_j \in S, x_j \in X, n \in \mathbb{N}\}.$$

As in Section 2, let G be a topological group, suppose that H acts on G and take the corresponding actions defined in Section 2:

$$H \times G \longrightarrow G \quad \text{and} \quad \cdot : (H \rtimes G) \times G \longrightarrow G.$$

Hence we define the skew product flow

$$\Psi : S \times (H \rtimes G) \times X \longrightarrow (H \rtimes G) \times X, \quad \Psi_s(h, g, x) := (\psi_s(h, g, x), sx) \quad (5.2)$$

with $\psi_s : (H \rtimes G) \times X \rightarrow H \rtimes G$ defined as

$$\psi_s(h, g, x) := (\phi_s(x)h, \phi_s(x)e_H g * a_s(x)) = (\phi_s(x)h, (\phi_s(x)e_H, a_s(x)) \cdot g),$$

where $a : S \times X \rightarrow G$ is a continuous map (a skewing map) satisfying

$$a(e_S, x) = e_G \text{ and } a_{s_1 \cdot s_2}(x) = \phi_{s_1}(s_2 x) e_H a_{s_2}(x) * a_{s_1}(s_2 x).$$

Now we define fundamental domains in this context.

Definition 5.1 Denote by R the topological group generated by S , that is, take R as the smallest group containing S . A *fundamental domain* for a skew product transformation semigroup $\Phi : S \times H \times X \rightarrow H \times X$ is a pair (Z, τ) where Z is a subset of $H \times X$ and $\tau : H \times X \rightarrow R$ is a continuous map such that for all $(h, x) \in H \times X$, it holds

$$\Phi(s, (h, x)) \in Z \text{ if and only if } s = \tau(x).$$

Then it is not difficult to prove the following generalization of Proposition 4.7.

Proposition 5.2 Take the skew product transformation semigroups Φ^i and Ψ^i , with $i = 1, 2$, as defined in (5.1) and (5.2). If there exist homeomorphic fundamental domains for Φ^i , $i = 1, 2$, then Ψ^1 is topologically conjugate to Ψ^2 .

Next we briefly discuss topological entropy in this context.

Consider a continuous skew product flow $\Phi : \mathbb{T} \times X \times B \rightarrow X \times B$ of the form (4.1) denoted by

$$\Phi_t(x, b) := (\phi_t(x, b), \vartheta_t b).$$

Suppose that X and B are metric spaces and B is compact. Furthermore, denote by $Q(b)$, $b \in B$, a uniformly bounded family of compact subsets of X .

Remark 5.3 Such a family may be viewed as an analogue to random sets in the theory of random dynamical systems; cf. Arnold [1].

Fix $b \in B$ and let $T, \varepsilon > 0$. Define a (T, ε) -spanning set $R(T, \varepsilon)$ by the following: for every $x \in Q(\vartheta_{-T} b)$ there is $y \in R$ with

$$d(\phi_t(x, \vartheta_{-T} b), \phi_t(y, \vartheta_{-T} b)) < \varepsilon \quad \text{for } t \in [0, T].$$

Let $r(T, \varepsilon)$ be the minimal cardinality of such a set and define the entropy in the fiber over b by

$$h(\varepsilon, b, Q(\cdot)) := \limsup_{T \rightarrow \infty} \frac{1}{T} \ln r(T, \varepsilon, b, Q(\cdot)), \quad h(b, Q(\cdot)) := \lim_{\varepsilon \searrow 0} h(\varepsilon, b, Q(\cdot)),$$

and, finally,

$$h := \sup_{b \in B} \sup_{Q(\cdot)} h(b, Q(\cdot))$$

We claim that this fiber entropy is invariant under skew conjugacy (for simplicity, we assume that the skew conjugacy is the identity on B).

Proposition 5.4 Suppose that Φ^1 and Φ^2 are skew conjugate and let $Q^1(b)$, $b \in B$ be as above. Define $Q^2(b) := h(Q^1(b), b)$, $b \in B$. Then for every $b \in B$

$$h_{\text{inv}}(b, Q^2(\cdot)) = h_{\text{inv}}(b, Q^1(\cdot)).$$

Proof. We know that

$$h(\phi^1(t, x, b), \vartheta_t b) = \phi^2(t, h(x, b), b).$$

It suffices to show that every $\varepsilon_2 > 0$ there is $\varepsilon_1 > 0$ such that for every $T > 0$ every (T, ε_1) -spanning set R for $Q^1(\cdot)$ is mapped to a (T, ε_2) -spanning set for $Q^2(\cdot)$. In fact, this implies $h_{\text{inv}}(\varepsilon_2, b, Q^2(\cdot)) \leq h_{\text{inv}}(\varepsilon_1, b, Q^1(\cdot))$ and hence $h_{\text{inv}}(b, Q^2(\cdot)) \leq h_{\text{inv}}(b, Q^1(\cdot))$; the assertion follows by interchanging the roles of $Q^1(\cdot)$ and $Q^2(\cdot)$. The rest is straightforward. \square

Acknowledgements The second author's research was partially supported by CNPq/Universal, grant n° 476024/2012–9, and by Fundação Araucária, grant n° 20134003. The authors also wish to thank the referees for their comments.

References

- [1] L. Arnold, *Random Dynamical Systems* (Springer-Verlag, Berlin, 1998), 586 pp.
- [2] V. Ayala, F. Colonius, and W. Kliemann, On topological equivalence of linear flows with applications to bilinear control systems, *J. Dyn. Control Syst.* **13**, 337–362 (2007).
- [3] F. Colonius and W. Kliemann, *Dynamical Systems and Linear Algebra* (American Mathematical Society, Providence, 2014), 284 pp.
- [4] F. Colonius and W. Kliemann, *The Dynamics of Control* (Birkhäuser, Boston, 2000), 634 pp.
- [5] F. Colonius and A. J. Santana, Topological conjugacy for affine-linear flows and control systems, *Comm. Pure Appl. Math.* **10**, 847–857 (2011).
- [6] R. Ellis, Cocycles in topological dynamics, *Topology* **17**, 111–130 (1978).
- [7] C. Kawan, O. G. Rocio and A. J. Santana, On topological conjugacy of left invariant flows on semisimple and affine Lie groups, *Proyecciones* **30**, 175–188 (2011).
- [8] A. S. Kechris, *Global Aspects of Ergodic Group Actions* (American Mathematical Society, Providence, 2010), 237 pp.
- [9] D. A. Lind, Split skew products, a related functional equation, and specification, *Israel J. Math.* **30**, 236–254 (1978).
- [10] M. Moskowitz and R. Sacksteder, The exponential map and differential equations on real Lie groups, *J. Lie Theory* **13**, 291–306 (2003).
- [11] J. A. Souza, On limit behavior of skew-product transformation semigroups, *Math. Nachr.* **287**, 91–104 (2013).