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On the solution set of a nonconvex nonclosed Sturm-Liouville type differential inclusion

Abstract. We consider a nonconvex and nonclosed Sturm-Liouville type differential inclusion and we prove the arcwise connectedness of the set of its solutions.

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1. Introduction. This paper is concerned with the following differential inclusion

$$(p(t)x'(t))' \in F(t, x(t), H(t, x(t))) \quad a.e.\ (I),\ x(0) = x_0,\ x'(0) = x_1, \tag{1.1}$$

where X is a real separable Banach space, $\mathcal{P}(X)$ is the family of all subsets of X, $I = [0, T]$, $F(.,.,.) : I \times X^2 \to \mathcal{P}(X)$, $H(.,.) : I \times X \to \mathcal{P}(X)$ and $p(.) : I \to (0, \infty)$ is continuous.

When F does not depend on the last variable, (1.1) reduces to

$$(p(t)x'(t))' \in F(t, x(t)) \quad a.e.\ (I), \quad x(0) = x_0, \quad x'(0) = x_1, \tag{1.2}$$

Existence results and qualitative properties of the solutions of problem (1.2) may be found in [4,5,6] etc. In all these papers the set-valued map F is assumed to be at least closed-valued. Such an assumption is quite natural in order to obtain good properties of the solution set, but it is interesting to investigate the problem when the right-hand side of the multivalued equation may have nonclosed values.

Following the approach in [8] we consider the problem (1.1), where F and H are closed-valued multifunctions Lipschitzian with respect to the second variable and F is contractive in the third variable. Obviously, the right-hand side of the differential inclusion in (1.1) is in general neither convex nor closed. We prove the arcwise connectedness of the solution set of problem (1.1). The main tool is a result ([7,8])

concerning the arcwise connectedness of the fixed point set of a class of nonconvex nonclosed set-valued contractions.

The paper is organized as follows: in Section 2 we recall some preliminary results that we use in the sequel and in Section 3 we prove our main result.

2. Preliminaries. Let Z be a metric space with the distance d_Z and let 2^Z be the family of all nonempty closed subsets of Z. For $a \in Z$ and $A, B \in 2^Z$ set $d_Z(a,B) = \inf_{b\in B} d_Z(a,b)$ and $d_Z^*(A,B) = \sup_{a\in A} d_Z(a,B)$. Denote by D_Z the Pompeiu-Hausdorff generalized metric on 2^Z defined by

$$D_Z(A,B) = \max\{d_Z^*(A,B), d_Z^*(B,A)\}, \quad A, B \in 2^Z.$$

In what follows, when the product $Z = Z_1 \times Z_2$ of metric spaces $Z_i, i = 1, 2$, is considered, it is assumed that Z is equipped with the distance $d_Z((z_1,z_2),(z_1',z_2')) = \sum_{i=1}^2 d_{Z_i}(z_i,z_i')$.

Let X be a nonempty set and let $F : X \to 2^Z$ be a set-valued map from X to Z. The range of F is the set $F(X) = \cup_{x\in X} F(x)$. Let $(X, \mathcal{F})$ be a measurable space. The multifunction $F : X \to 2^Z$ is called measurable if $F^{-1}(\Omega) \in \mathcal{F}$ for any open set $\Omega \subset Z$, where $F^{-1}(\Omega) = \{x \in X; F(x) \cap \Omega \neq \emptyset\}$. Let (X, d_X) be a metric space. The multifunction F is called Hausdorff continuous if for any $x_0 \in X$ and every $\epsilon > 0$ there exists $\delta > 0$ such that $x \in X, d_X(x,x_0) < \delta$ implies $D_Z(F(x), F(x_0)) < \epsilon$.

Let $(T, \mathcal{F}, \mu)$ be a finite, positive, nonatomic measure space and let $(X, |.|_X)$ be a Banach space. We denote by $L^1(T,X)$ the Banach space of all (equivalence classes of) Bochner integrable functions $u : T \to X$ endowed with the norm

$$|u|_{L^1(T,X)} = \int_T |u(t)|_X d\mu$$

A nonempty set $K \subset L^1(T,X)$ is called decomposable if, for every $u, v \in K$ and every $A \in \mathcal{F}$, one has

$$\chi_A.u + \chi_{T\setminus A}.v \in K$$

where $\chi_B, B \in \mathcal{F}$ indicates the characteristic function of B.

A metric space Z is called an absolute retract if, for any metric space X and any nonempty closed set $X_0 \subset X$, every continuous function $g : X_0 \to Z$ has a continuous extension $g : X \to Z$ over X. It is obvious that every continuous image of an absolute retract is an arcwise connected space.

In what follows we recall some preliminary results that are the main tools in the proof of our result.

Let $(T, \mathcal{F}, \mu)$ be a finite, positive, nonatomic measure space, S a separable Banach space and let $(X, |.|_X)$ be a real Banach space. To simplify the notation we write E in place of $L^1(T,X)$.

Lemma 2.1 ([8]) *Assume that $\phi : S \times E \to 2^E$ and $\psi : S \times E \times E \to 2^E$ are Hausdorff continuous multifunctions with nonempty, closed, decomposable values, satisfying the following conditions*

a) *There exists $L \in [0,1)$ such that, for every $s \in S$ and every $u, u' \in E$,*

$$D_E(\phi(s,u), \phi(s,u')) \leqslant L|u - u'|_E.$$

b) *There exists* $M \in [0,1)$ *such that* $L + M < 1$ *and for every* $s \in S$ *and every* $(u,v),(u',v') \in E \times E$,

$$D_E(\psi(s,u,v),\psi(s,u',v')) \leqslant M(|u-u'|_E + |v-v'|_E).$$

Set $Fix(\Gamma(s,.)) = \{u \in E; u \in \Gamma(s,u)\}$, *where* $\Gamma(s,u) = \psi(s,u,\phi(s,u))$, $(s,u) \in S \times E$. *Then*

1) *For every* $s \in S$ *the set* $Fix(\Gamma(s,.))$ *is nonempty and arcwise connected.*

2) *For any* $s_i \in S$, *and any* $u_i \in Fix(\Gamma(s,.)), i = 1,...,p$ *there exists a continuous function* $\gamma : S \to E$ *such that* $\gamma(s) \in Fix(\Gamma(s,.))$ *for all* $s \in S$ *and* $\gamma(s_i) = u_i, i = 1,...,p$.

Lemma 2.2 ([8]) *Let* $U : T \to 2^X$ *and* $V : T \times X \to 2^X$ *be two nonempty closed-valued multifunctions satisfying the following conditions*

a) U *is measurable and there exists* $r \in L^1(T)$ *such that* $D_X(U(t),\{0\}) \leqslant r(t)$ *for almost all* $t \in T$.

b) *The multifunction* $t \to V(t,x)$ *is measurable for every* $x \in X$.

c) *The multifunction* $x \to V(t,x)$ *is Hausdorff continuous for all* $t \in T$.

Let $v : T \to X$ *be a measurable selection from* $t \to V(t,U(t))$. *Then there exists a selection* $u \in L^1(T,X)$ *such that* $v(t) \in V(t,u(t)), t \in T$.

In the sequel $I = [0,T]$, X is a real separable Banach space with norm $|.|$, and with the corresponding metric $d(.,.)$.

Consider $F : I \times X \to \mathcal{P}(X)$ a set-valued map, $x_0, x_1 \in X$ and $p(.) : I \to (0,\infty)$ a continuous mapping that defined the Cauchy problem (1.1).

A continuous mapping $x(.) \in C(I,X)$ is called a solution of problem (1.1) if there exists a (Bochner) integrable function $f(.) \in L^1(I,X)$ such that:

$$f(t) \in F(t,x(t)) \quad a.e. \,(I), \tag{2.1}$$

$$x(t) = x_0 + p(0)x_1 \int_0^t \frac{1}{p(s)} ds + \int_0^t \frac{1}{p(s)} \int_0^s f(u) du ds \quad \forall t \in I. \tag{2.2}$$

Note that, if we denote $G(t,u) := \int_u^t \frac{1}{p(s)}$, $t \in I$, then (2.2) may be rewrite as

$$x(t) = x_0 + p(0)x_1 G(t,0) + \int_0^t G(t,u) f(u) du \quad \forall t \in I, \tag{2.3}$$

We shall use the following notations for the solution sets of (1.1).

$$\mathcal{S}(x_0,x_1) = \{x(.); \quad x(.) \text{ is a solution of (1.1)}\}. \tag{2.4}$$

In order to study problem (1.1) we introduce the following hypothesis.

Hypothesis 2.3 *$F: I\times X\times X \to \mathcal{P}(X)$ and $H: I\times X \to \mathcal{P}(X)$ are two set-valued maps with nonempty closed values, satisfying*

i) *The set-valued maps $t \to F(t,u,v)$ and $t \to H(t,u)$ are measurable for all $u,v \in X$.*

ii) *There exist $l(.) \in L^1(I,R)$ such that, for every $u,u' \in X$,*

$$D(H(t,u),H(t,u')) \leqslant l(t)|u-u'| \quad a.e.\ (I).$$

iii) There exist $m(.) \in L^1(I,R)$ and $\theta \in [0,1)$ such that, for every $u,v,u',v' \in X$,

$$D(F(t,u,v),F(t,u',v')) \leqslant m(t)|u-u'| + \theta|v-v'| \quad a.e.\ (I).$$

iv) There exist $f,g \in L^1(I,R)$ such that

$$d(0,F(t,0,0)) \leqslant f(t), \quad d(0,H(t,0)) \leqslant g(t) \quad a.e.\ (I).$$

In what follows $N(t) = \max\{l(t),m(t)\}$, $t \in I$, $N^*(t) = \int_0^t N(s)ds$ and $M := \sup_{t\in I}\frac{1}{p(t)}$. Note that $|G(t,u)| \leqslant Mt\ \forall t,u \in I, u \leqslant t$.

Given $\alpha \in R$ we denote by L^1 the Banach space of all (equivalence classes of) Lebesgue measurable functions $\sigma: I \to X$ endowed with the norm

$$|\sigma|_1 = \int_0^T e^{-\alpha N^*(t)}|\sigma(t)|dt.$$

3. Main results. Even if the multifunction from the right-hand side of (1.1) and has, in general, nonclosed nonconvex values, its solution set $\mathcal{S}(x_0,x_1)$ defined in (2.4) has some meaningful properties, stated in theorem below.

Theorem 3.1 *Assume that F and H satisfy Hypothesis 2.3 and let $\alpha > \frac{2MT}{1-\theta}$. Then*

1) *For every $(x_0,x_1) \in X\times X$, the solution set $\mathcal{S}(x_0,x_1)$ is nonempty and arcwise connected in the space C(I,X).*

2) *) For any $(\xi_i,\mu_i) \in X\times X$ and any $x_i \in \mathcal{S}(\xi_i,\mu_i)$, $i = 1,...,p$, there exists a continuous function $s: X\times X \to C(I,X)$ such that $s(\xi,\mu) \in \mathcal{S}(\xi,\mu)$ for any $(\xi,\mu) \in X\times X$ and $s(\xi_i,\mu_i) = x_i, i = 1,...,p$.*

3) *The set $\mathcal{S} = \cup_{(\xi,\mu)\in X\times X}\mathcal{S}(\xi,\mu)$ is arcwise connected in C(I,X).*

Proof 1) For $(\xi,\mu) \in X\times X$ and $u \in L^1$, set

$$x_{\xi,\mu}(t) = \xi + p(0)G(t,0)\mu + \int_0^t G(t,s)u(s)ds, \quad t \in I$$

and consider $\lambda: X\times X \to C(I,X)$ defined by $\lambda(\xi,\mu)(t) = \xi + p(0)G(t,0)\mu$.

We prove that the multifunctions $\phi : X \times X \times L^1 \to 2^{L^1}$ and $\psi : X \times X \times \times L^1 \times L^1 \to 2^{L^1}$ given by

$$\phi((\xi,\mu),u) = \{v \in L^1; \quad v(t) \in H(t, x_{\xi,\mu}(t)) \quad a.e.(I)\},$$

$$\psi((\xi,\mu),u,v) = \{w \in L^1; \quad w(t) \in F(t, x_{\xi,\mu}(t), v(t)) \quad a.e.(I)\},$$

$(\xi,\mu) \in X \times X$, $u, v \in L^1$ satisfy the hypotheses of Lemma 2.1.

Since $x_{\xi,\mu}(.)$ is measurable and H satisfies Hypothesis 2.3 i) and ii), the multifunction $t \to H(t, x_{\xi,\mu}(t))$ is measurable and nonempty closed-valued, it has a measurable selection. Therefore due to Hypothesis 2.3 iv), the set $\phi((\xi,\mu),u)$ is nonempty. The fact that the set $\phi((\xi,\mu),u)$ is closed and decomposable follows by a simple computation. In the same way we obtain that $\psi((\xi,\mu),u,v)$ is a nonempty closed decomposable set.

Pick $((\xi,\mu),u), ((\xi_1,\mu_1),u_1) \in X \times X \times L^1$ and choose $v \in \phi((\xi,\mu),u)$. For each $\varepsilon > 0$ there exists $v_1 \in \phi((\xi_1,\mu_1),u_1)$ such that, for every $t \in I$, one has

$$|v(t) - v_1(t)| \leqslant D(H(t, x_{\xi,\mu}(t)), H(t, x_{\xi_1,\mu_1}(t))) + \varepsilon \leqslant$$

$$l(t)[|\xi - \xi_1| + p(0)MT|\mu - \mu_1| + MT\int_0^t |u(s) - u_1(s)|ds] + \varepsilon.$$

Hence

$$|v - v_1|_1 \leqslant [|\xi - \xi_1| + p(0)MT|\mu - \mu_1|]\int_0^T e^{-\alpha N^*(t)} l(t)dt + MT\int_0^T e^{-\alpha N^*(t)}$$

$$l(t)(\int_0^t |u(s) - u_1(s)|ds)dt + \varepsilon T \leqslant \frac{1}{\alpha}[|\xi - \xi_1| + p(0)MT|\mu - \mu_1|] + \frac{MT}{\alpha}|u - u_1|_1$$

$+\varepsilon T$ for any $\varepsilon > 0$.

This implies

$$d_{L^1}(v, \phi((\xi_1,\mu_1),u_1)) \leqslant \frac{1}{\alpha}[|\xi - \xi_1| + p(0)MT|\mu - \mu_1|] + \frac{MT}{\alpha}|u - u_1|_1$$

for all $v \in \phi((\xi,\mu),u)$. Therefore,

$$d^*_{L^1}(\phi((\xi,\mu),u), \phi((\xi_1,\mu_1),u_1)) \leqslant \frac{1}{\alpha}[|\xi - \xi_1| + p(0)MT|\mu - \mu_1|] + \frac{MT}{\alpha}|u - u_1|_1$$

Consequently,

$$D_{L^1}(\phi((\xi,\mu),u), \phi((\xi_1,\mu_1),u_1)) \leqslant \frac{1}{\alpha}[|\xi - \xi_1| + p(0)MT|\mu - \mu_1|] + \frac{MT}{\alpha}|u - u_1|_1$$

which shows that ϕ is Hausdorff continuous and satisfies the assumptions of Lemma 2.1.

Pick $((\xi,\mu),u,v), ((\xi_1,\mu_1),u_1,v_1) \in X \times X \times L^1 \times L^1$ and choose $w \in \psi((\xi,\mu),u,v)$. Then, as before, for each $\varepsilon > 0$ there exists $w_1 \in \psi((\xi_1,\mu_1),u_1,$
$v_1)$ such that for every $t \in I$

$$|w(t)-w_1(t)|\leqslant D(F(t,x_{\xi,\mu}(t),v(t)),F(t,x_{\xi_1,\mu_1}(t),v_1(t)))+\varepsilon\leqslant$$

$$m(t)[|\xi-\xi_1|+p(0)MT|\mu-\mu_1|+MT\int_0^t|u(s)-u_1(s)|ds]+\theta|v(t)-v_1(t)|+\varepsilon.$$

Hence

$$|w-w_1|_1\leqslant\frac{1}{\alpha}[|\xi-\xi_1|+p(0)MT|\mu-\mu_1|]+\frac{MT}{\alpha}|u-u_1|_1+\theta|v-v_1|_1+\varepsilon T$$

$$\leqslant\frac{1}{\alpha}[|\xi-\xi_1|+p(0)MT|\mu-\mu_1|]+(\frac{MT}{\alpha}+\theta)(|u-u_1|_1+|v-v_1|_1)+\varepsilon T$$

$$\leqslant\frac{1}{\alpha}[|\xi-\xi_1|+p(0)MT|\mu-\mu_1|]+(\frac{MT}{\alpha}+\theta)d_{L^1\times L^1}((u,v),(u_1,v_1))+\varepsilon T.$$

As above, we deduce that

$$D_{L^1}(\psi((\xi,\mu),u,v),\psi((\xi_1,\mu_1),u_1,v_1))\leqslant$$

$$\frac{1}{\alpha}[|\xi-\xi_1|+p(0)MT|\mu-\mu_1|]+(\frac{MT}{\alpha}+\theta)d_{L^1\times L^1}((u,v),(u_1,v_1)).$$

namely, the multifunction ψ is Hausdorff continuous and satisfies the hypothesis of Lemma 2.1.

Define $\Gamma((\xi,\mu),u)=\psi((\xi,\mu),u,\phi((\xi,\mu),u)),((\xi,\mu),u)\in X^2\times L^1$. According to Lemma 2.1, the set $Fix(\Gamma((\xi,\mu),.))=\{u\in L^1;u\in\Gamma((\xi,\mu),u)\}$ is nonempty and arcwise connected in $L^1(I,X)$. Moreover, for fixed $(\xi_i,\mu_i)\in X^2$ and $u_i\in Fix(\Gamma((\xi_i,\mu_i),.)),i=1,...,p$, there exists a continuous function $\gamma:X^2\to L^1$ such that

$$\gamma((\xi,\mu))\in Fix(\Gamma((\xi,\mu),.)),\quad\forall(\xi,\mu)\in X^2,\tag{3.2}$$

$$\gamma((\xi_i,\mu_i))=u_i,\quad i=1,...,p.\tag{3.3}$$

We shall prove that

$$Fix(\Gamma((\xi,\mu),.))=\{u\in L^1;\quad u(t)\in F(t,x_{\xi,\mu}(t),H(t,x_{\xi,\mu}(t)))\quad a.e.\ (I)\}.\tag{3.4}$$

Denote by $A(\xi,\mu)$ the right-hand side of (3.4). If $u\in Fix(\Gamma((\xi,\mu),.))$ then there is $v\in\phi((\xi,\mu),v)$ such that $u\in\psi((\xi,\mu),u,v)$. Therefore, $v(t)\in H(t,x_{\xi,\mu}(t))$ and

$$u(t)\in F(t,x_{\xi,\mu}(t),v(t))\subset F(t,x_{\xi,\mu}(t),H(t,x_{\xi,\mu}(t)))\quad a.e.\ (I),$$

so that $Fix(\Gamma((\xi,\mu),.))\subset A(\xi,\mu)$.

Let now $u\in A(\xi,\mu)$. By Lemma 2.2, there exists a selection $v\in L^1$ of the multifunction $t\to H(t,x_{\xi,\mu}(t))$ satisfying

$$u(t)\in F(t,x_{\xi,\mu}(t),v(t))\quad a.e.\ (I).$$

Hence, $v\in\phi((\xi,\mu),v)$, $u\in\psi((\xi,\mu),u,v)$ and thus $u\in\Gamma((\xi,\mu),u)$, which completes the proof of (3.4).

We next note that the function $T : L^1 \to C(I, X)$,

$$T(u)(t) := \int_0^t G(t,s)u(s)ds$$

is continuous and one has

$$\mathcal{S}(\xi,\mu) = \lambda(\xi,\mu) + T(Fix(\Gamma((\xi,\mu),.))), \quad (\xi,\mu) \in X^2. \tag{3.5}$$

Since $Fix(\Gamma((\xi,\mu),.))$ is nonempty and arcwise connected in L^1, the set $\mathcal{S}(\xi,\mu)$ has the same properties in $C(I, X)$.

2) Let $(\xi_i,\mu_i) \in X^2$ and let $x_i \in \mathcal{S}(\xi_i,\mu_i), i = 1,...,p$ be fixed. By (3.5) there exists $v_i \in Fix(\Gamma((\xi_i,\mu_i),.))$ such that

$$x_i = \lambda(\xi_i,\mu_i) + T(v_i), \quad i = 1,...,p.$$

If $\gamma : X^2 \to L^1$ is a continuous function satisfying (3.2) and (3.3) we define, for every $(\xi,\mu) \in X^2$,

$$s(\xi,\mu) = \lambda(\xi,\mu) + T(\gamma(\xi,\mu)).$$

Obviously, the function $s : X \to C(I, X)$ is continuous, $s(\xi,\mu) \in \mathcal{S}(\xi,\mu)$ for all $(\xi,\mu) \in X^2$ and

$$s(\xi_i,\mu_i) = \lambda(\xi_i,\mu_i) + T(\gamma(\xi_i,\mu_i)) = \lambda(\xi_i,\mu_i) + T(v_i) = x_i, \quad i = 1,...,p.$$

3) Let $x_1, x_2 \in \mathcal{S} = \cup_{(\xi,\mu)\in X^2}\mathcal{S}(\xi,\mu)$ and choose $(\xi_i,\mu_i) \in X^2$, $i = 1, 2$ such that $x_i \in S(\xi_i,\mu_i)$, $i = 1, 2$. From the conclusion of 2) we deduce the existence of a continuous function $s : X^2 \to C(I, X)$ satisfying $s(\xi_i,\mu_i) = x_i$, $i = 1, 2$ and $s(\xi,\mu) \in \mathcal{S}(\xi,\mu)$, $(\xi,\mu) \in X^2$. Let $h : [0, 1] \to X^2$ be a continuous mapping such that $h(0) = (\xi_1,\mu_1)$ and $h(1) = (\xi_2,\mu_2)$. Then the function $s \circ h : [0, 1] \to C(I, X)$ is continuous and verifies

$$s \circ h(0) = x_1, \quad s \circ h(1) = x_2, \quad s \circ h(\tau) \in \mathcal{S}(h(\tau)) \subset \mathcal{S}, \quad \tau \in [0, 1].$$

This finishes the proof. ■

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