EXISTENCE RESULTS FOR SYSTEMS WITH NONLINEAR COUPLED NONLOCAL INITIAL CONDITIONS

OCTAVIA BOLOJAN-NICA, GENNARO INFANTE, AND RADU PRECUP

Abstract. The purpose of the present work is to study the existence of solutions to initial value problems for nonlinear first order differential systems with nonlinear nonlocal boundary conditions of functional type. The existence results are established by means of the Perov, Schauder and Leray-Schauder fixed point principles combined with a technique based on vector-valued metrics and convergent to zero matrices.

1. Introduction

Nonlocal problems for different classes of differential equations and systems are intensively studied in the literature by a variety of methods (see for example [3, 4, 5, 10, 11, 12, 13, 15, 16, 36, 38, 42, 45, 48, 49, 50, 51, 52, 53, 54] and references therein). For problems with nonlinear boundary conditions we refer the reader to [1, 18, 19, 20, 22, 25, 26, 27, 29, 31, 33, 34, 44] and references therein.

In this paper we extend the results from [9, 39, 41], in order to deal with the nonlocal initial value problem for the first order differential system

\[
\begin{aligned}
x'(t) &= f_1(t, x(t), y(t)), \\
y'(t) &= f_2(t, x(t), y(t)), & \text{ on } [0, 1], \\
x(0) &= \alpha[x, y], \\
y(0) &= \beta[x, y].
\end{aligned}
\]

(1.1)

Here, \( f_1, f_2 : [0, 1] \times \mathbb{R}^2 \to \mathbb{R} \) are continuous functions and \( \alpha, \beta : (C[0, 1])^2 \to \mathbb{R} \) are nonlinear continuous functionals.

Remark 1.1. We can also consider the case when \( f_1, f_2 \) are \( L^1 \)-Carathéodory functions and \( \alpha, \beta : (W^{1,1}(0, 1))^2 \to \mathbb{R} \). In this case, the system (1.1) can be defined a.e. on \([0, 1]\) and the solutions can be sought in the Sobolev space \((W^{1,1}(0, 1))^2\).

2010 Mathematics Subject Classification. Primary 34A34, secondary 34A12, 34B10, 47H10.

Key words and phrases. Nonlinear differential system, nonlocal boundary condition, nonlinear boundary condition, fixed point, vector-valued norm, convergent to zero matrix.
Our approach is to rewrite the problem \((1.1)\) as a system of the form
\[
\begin{align*}
  x_a &= \left( a + \int_0^t f_1(s, x(s), y(s)) \, ds, \, \alpha [x, y] \right), \\
  y_b &= \left( b + \int_0^t f_2(s, x(s), y(s)) \, ds, \, \beta [x, y] \right),
\end{align*}
\]
where by \(x_a, y_b\) we mean the pairs \((x, a), (y, b) \in C[0, 1] \times \mathbb{R}\).

This, in turn, can be viewed as a fixed point problem in \((C[0, 1] \times \mathbb{R})^2\) for the completely continuous operator
\[
T = (T_1, T_2) : (C[0, 1] \times \mathbb{R})^2 \to (C[0, 1] \times \mathbb{R})^2,
\]
where \(T_1\) and \(T_2\) are given by
\[
T_1 [x_a, y_b] = \left( a + \int_0^t f_1(s, x(s), y(s)) \, ds, \, \alpha [x, y] \right),
\]
\[
T_2 [x_a, y_b] = \left( b + \int_0^t f_2(s, x(s), y(s)) \, ds, \, \beta [x, y] \right).
\]

In what follows, we introduce some notations, definitions and basic results which are used throughout this paper. Three different fixed point principles are used in order to prove the existence of solutions for the problem \((1.1)\), namely the fixed point principles of Perov, Schauder and Leray-Schauder (see \([45, 46]\)). A technique that makes use of the vector-valued metrics and convergent to zero matrices has an essential role in all three cases. Therefore, we recall the fundamental results that are used in the next sections (see \([2, 43, 45]\)).

Let \(X\) be a nonempty set.

**Definition 1.2.** By a vector-valued metric on \(X\) we mean a mapping \(d : X \times X \to \mathbb{R}_+^n\) such that

(i) \(d(u, v) \geq 0\) for all \(u, v \in X\) and if \(d(u, v) = 0\) then \(u = v\);

(ii) \(d(u, v) = d(v, u)\) for all \(u, v \in X\);

(iii) \(d(u, v) \leq d(u, w) + d(w, v)\) for all \(u, v, w \in X\).

Here, if \(x, y \in \mathbb{R}^n, x = (x_1, x_2, \ldots, x_n), y = (y_1, y_2, \ldots, y_n),\) by \(x \leq y\) we mean \(x_i \leq y_i\) for \(i = 1, 2, \ldots, n\). We call the pair \((X, d)\) a generalised metric space. For such a space convergence and completeness are similar to those in usual metric spaces.

**Definition 1.3.** A square matrix \(M\) with nonnegative elements is said to be convergent to zero if
\[
M^k \to 0 \quad \text{as} \quad k \to \infty.
\]
The property of being convergent to zero is equivalent to each of the following conditions from the characterisation lemma below (see [7, pp 9, 10], [45], [46], [47, pp 12, 88]):

**Lemma 1.4.** Let $M$ be a square matrix of nonnegative numbers. The following statements are equivalent:

(i) $M$ is a matrix convergent to zero;
(ii) $I - M$ is nonsingular and $(I - M)^{-1} = I + M + M^2 + \ldots$ (where $I$ stands for the unit matrix of the same order as $M$);
(iii) the eigenvalues of $M$ are located inside the unit disc of the complex plane;
(iv) $I - M$ is nonsingular and $(I - M)^{-1}$ has nonnegative elements.

Note that, according to the equivalence of the statements (i) and (iv), a matrix $M$ is convergent to zero if and only if the matrix $I - M$ is inverse-positive.

The following lemma is a consequence of the previous characterisations.

**Lemma 1.5.** Let $A$ be a matrix that is convergent to zero. Then for each matrix $B$ of the same order whose elements are nonnegative and sufficiently small, the matrix $A + B$ is also convergent to zero.

**Definition 1.6.** Let $(X, d)$ be a generalized metric space. An operator $T : X \to X$ is said to be **contractive** (with respect to the vector-valued metric $d$ on $X$) if there exists a convergent to zero (Lipschitz) matrix $M$ such that

$$d(T(u), T(v)) \leq Md(u, v) \quad \text{for all } u, v \in X.$$  

**Theorem 1.7** (Perov). Let $(X, d)$ be a complete generalized metric space and $T : X \to X$ a contractive operator with Lipschitz matrix $M$. Then $T$ has a unique fixed point $u^*$ and for each $u_0 \in X$ we have

$$d(T^k(u_0), u^*) \leq M^k(I - M)^{-1}d(u_0, T(u_0)) \quad \text{for all } k \in \mathbb{N}.$$  

**Theorem 1.8** (Schauder). Let $X$ be a Banach space, $D \subset X$ a nonempty closed bounded convex set and $T : D \to D$ a completely continuous operator (i.e., $T$ is continuous and $T(D)$ is relatively compact). Then $T$ has at least one fixed point.

**Theorem 1.9** (Leray–Schauder). Let $(X, \| \cdot \|_X)$ be a Banach space, $R > 0$ and $T : \overline{B}_X(0; R) \to X$ a completely continuous operator. If $\|u\|_X < R$ for every solution $u$ of the equation $u = \lambda T(u)$ and any $\lambda \in (0, 1)$, then $T$ has at least one fixed point.

In this paper, by $|x|_C$, where $x \in C[0, 1]$, we mean

$$|x|_C = \max_{t \in [0,1]} |x(t)|.$$
Also, throughout the paper we shall assume that $f_1, f_2 : [0, 1] \times \mathbb{R}^2 \to \mathbb{R}$ are such that $f_1(\cdot, x, y), f_2(\cdot, x, y)$ are measurable for each $(x, y) \in \mathbb{R}^2$ and $f_1(t, \cdot, \cdot), f_2(t, \cdot, \cdot)$ are continuous for almost all $t \in [0, 1]$.

2. Existence and Uniqueness of the Solution

In this section we show that the existence of solutions to the problem (1.1) follows from Perov’s fixed point theorem in case that the nonlinearities $f_1, f_2$ and the functionals $\alpha, \beta$ satisfy Lipschitz conditions of the type:

\begin{equation}
\begin{cases}
|f_1(t, x, y) - f_1(t, \overline{x}, \overline{y})| \leq a_1 |x - \overline{x}| + b_1 |y - \overline{y}|
\\
|f_2(t, x, y) - f_2(t, \overline{x}, \overline{y})| \leq a_2 |x - \overline{x}| + b_2 |y - \overline{y}|,
\end{cases}
\end{equation}

for all $x, y, \overline{x}, \overline{y} \in \mathbb{R}$, and

\begin{equation}
\begin{cases}
|\alpha[x, y] - \alpha[\overline{x}, \overline{y}]| \leq A_1 |x - \overline{x}|_C + B_1 |y - \overline{y}|_C
\\
|\beta[x, y] - \beta[\overline{x}, \overline{y}]| \leq A_2 |x - \overline{x}|_C + B_2 |y - \overline{y}|_C,
\end{cases}
\end{equation}

for all $x, y, \overline{x}, \overline{y} \in C[0, 1]$.

For a given number $\theta > 0$, denote

\begin{align*}
    m_{11}(\theta) &= \max \left\{ \frac{1}{\theta}, a_1 + \theta A_1 \right\} \quad m_{12}(\theta) = b_1 + \theta B_1 \\
    m_{21}(\theta) &= a_2 + \theta A_2 \quad m_{22}(\theta) = \max \left\{ \frac{1}{\theta}, b_2 + \theta B_2 \right\}.
\end{align*}

**Theorem 2.1.** Assume that $f_1, f_2$ satisfy the Lipschitz conditions (2.1) and $\alpha, \beta$ satisfy conditions (2.2). In addition assume that for some $\theta > 0$, the matrix

\begin{equation}
M_\theta = \begin{bmatrix}
    m_{11}(\theta) & m_{12}(\theta) \\
    m_{21}(\theta) & m_{22}(\theta)
\end{bmatrix}
\end{equation}

is convergent to zero. Then the problem (1.1) has a unique solution.

**Proof.** We shall apply Perov’s fixed point theorem in $(C [0, 1] \times \mathbb{R})^2$ endowed with the vector-valued norm $\|\cdot\|_{(C[0,1] \times \mathbb{R})^2}$,

\[ \|u\|_{(C[0,1] \times \mathbb{R})^2} = \begin{bmatrix} |x_a| \\ |y_b| \end{bmatrix}, \]

for $u = (x_a, y_b)$. Here

\[ |x_a| = |(x, a)| = |x|_C + \theta |a|, \]

which represents a norm on $C[0, 1] \times \mathbb{R}$. We have to prove that $T$ is contractive with respect to the convergent to zero matrix $M_\theta$, more exactly that

\[ \|T(u) - T(\overline{u})\|_{(C[0,1] \times \mathbb{R})^2} \leq M_\theta \|u - \overline{u}\|_{(C[0,1] \times \mathbb{R})^2}, \]
for all $u = (x_a, y_b), \bar{u} = (\bar{x}, \bar{y}) \in (C[0, 1] \times \mathbb{R})^2$. Indeed, we have

$$
|T_1 [x_a, y_b] - T_1 [\bar{x}, \bar{y}]| \\
\leq \left| \int_0^1 \left| f_1 (s, x(s), y(s)) - f_1 (s, \bar{x}(s), \bar{y}(s)) \right| ds \right|_C + |a - \bar{a}| + \theta |\alpha | - \alpha| \bar{x}, \bar{y}]|
$$

\begin{align*}
\leq & a_1 \int_0^t |x(s) - \bar{x}(s)| ds + b_1 \int_0^t |y(s) - \bar{y}(s)| \left| + \theta A_1 |x - \bar{x}|_C + \theta B_1 |y - \bar{y}|_C + |a - \bar{a}| \right| \\
\leq & (a_1 + \theta A_1) |x - \bar{x}|_C + (b_1 + \theta B_1) |y - \bar{y}|_C + \left| \frac{1}{\theta} \cdot \theta |a - \bar{a}| \right|
\end{align*}

\begin{align*}
\leq & \max \left\{ \frac{1}{\theta} a_1 + \theta A_1 \right\} |x - \bar{x}| + (b_1 + \theta B_1) |y - \bar{y}|_C \\
= & m_{11} (\theta) |x - \bar{x}| + m_{12} (\theta) |y - \bar{y}|_C. \\
&(2.4)
\end{align*}

Similarly, we have

$$
|T_2 [x_a, y_b] - T_2 [\bar{x}, \bar{y}]| \\
\leq \left( a_2 + \theta A_2 \right) |x_a - \bar{x}| + \max \left\{ \frac{1}{\theta} b_2 + \theta B_2 \right\} |y_b - \bar{y}|_C
$$

\begin{align*}
|T_2 [x_a, y_b] - T_2 [\bar{x}, \bar{y}]| \\
\leq & m_{21} (\theta) |x_a - \bar{x}| + m_{22} (\theta) |y_b - \bar{y}|_C. \\
&(2.5)
\end{align*}

Now, both inequalities (2.4), (2.5) can be put together and be rewritten equivalently as

$$
\left[ \begin{array}{c}
|T_1 [x_a, y_b] - T_1 [\bar{x}, \bar{y}]| \\
|T_2 [x_a, y_b] - T_2 [\bar{x}, \bar{y}]|
\end{array} \right] \leq M_\theta \left[ \begin{array}{c}
x_a - \bar{x} \\
y_b - \bar{y}_C
\end{array} \right]
$$

or using the vector-valued norm

$$
\| T(u) - T(\bar{u}) \|_{(C[0, 1] \times \mathbb{R})^2} \leq M_\theta \| u - \bar{u} \|_{(C[0, 1] \times \mathbb{R})^2},
$$

where $M_\theta$ is given by (2.3) and assumed to be convergent to zero. The result follows now from Perov’s fixed point theorem.

3. Existence of at least one solution

In the beginning of this section, we give an application of Schauder’s fixed point theorem. More precisely, we show that the existence of solutions to the problem (1.1) follows from Schauder’s fixed point theorem in case that $f_1, f_2$ satisfy some relaxed growth condition of the type:

$$
|f_1 (t, x, y)| \leq a_1 |x| + b_1 |y| + c_1,
$$

$$
|f_2 (t, x, y)| \leq a_2 |x| + b_2 |y| + c_2,
$$

(3.1)
for all \(x, y, \overline{x}, \overline{y} \in \mathbb{R}\), and
\[
\begin{aligned}
|\alpha [x, y]| & \leq A_1 |x|_C + B_1 |y|_C + C_1, \\
|\beta [x, y]| & \leq A_2 |x|_C + B_2 |y|_C + C_2,
\end{aligned}
\]
for all \(x, y, \overline{x}, \overline{y} \in C[0, 1]\).

**Theorem 3.1.** If the conditions (3.1), (3.2) hold and the matrix (2.3) is convergent to zero for some \(\theta > 0\), then the problem (1.1) has at least one solution.

**Proof.** In order to apply Schauder’s fixed point theorem, we look for a nonempty, bounded, closed and convex subset \(B\) of \((C[0, 1] \times \mathbb{R})^2\) so that \(T(B) \subset B\). Let \(x_a, y_b\) be any elements of \(C[0, 1] \times \mathbb{R}\).

Then, using the same norm on \(C[0, 1] \times \mathbb{R}\) as in the proof of the previous theorem, we obtain
\[
T_1 [x_a, y_b] = \left[ a + \int_0^t f_1 (s, x (s), y (s)) \, ds \right] + \theta |x| = a + \int_0^t \left( a_1 |x(s)| + b_1 |y(s)| + c_1 \right) \, ds + \theta A_1 |x| + \theta B_1 |y| + \theta C_1
\]
\[
\leq a_1 |x| + b_1 |y| + c_1 + \theta A_1 |x| + \theta B_1 |y| + \theta C_1
\]
\[
= (a_1 + \theta A_1) |x| + (b_1 + \theta B_1) |y| + \theta |a| + c_1 + \theta C_1
\]
\[
\leq \max \left\{ \frac{1}{\theta} a_1 + \theta A_1 \right\} |x| + (b_1 + \theta B_1) |y| + c_0
\]
\[
= m_{11} (\theta) |x| + m_{12} (\theta) |y| + c_0,
\]
where \(c_0 := c_1 + \theta C_1\). Similarly
\[
T_2 [x_a, y_b] \leq (a_2 + \theta A_2) |x| + \max \left\{ \frac{1}{\theta} b_2 + \theta B_2 \right\} |y| + C_0
\]
\[
= m_{21} (\theta) |x| + m_{22} (\theta) |y| + C_0,
\]
where \(C_0 := c_2 + \theta C_2\). Now, from (3.3), (3.4) we have
\[
\begin{bmatrix}
|T_1 [x_a, y_b]| \\
|T_2 [x_a, y_b]| 
\end{bmatrix} \leq M_\theta \begin{bmatrix}
|x| \\
|y|
\end{bmatrix} + \begin{bmatrix}
c_0 \\
C_0
\end{bmatrix},
\]
where \(M_\theta\) is given by (2.3) and is assumed to be convergent to zero. Next we look for two positive numbers \(R_1, R_2\) such that if \(|x| \leq R_1\) and \(|y| \leq R_2\), then \(|T_1 [x_a, y_b]| \leq R_1, |T_2 [x_a, y_b]| \leq R_2\). To this end it is sufficient that
\[
M_\theta \begin{bmatrix}
R_1 \\
R_2
\end{bmatrix} + \begin{bmatrix}
c_0 \\
C_0
\end{bmatrix} \leq \begin{bmatrix}
R_1 \\
R_2
\end{bmatrix},
\]
whence
\[
\begin{bmatrix}
R_1 \\
R_2
\end{bmatrix} \geq (I - M_\theta)^{-1}
\begin{bmatrix}
c_0 \\
C_0
\end{bmatrix}.
\]

Notice that \( I - M_\theta \) is invertible and its inverse \((I - M_\theta)^{-1}\) has nonnegative elements since \( M_\theta \) is convergent to zero. Thus, if \( B = B_1 \times B_2 \), where

\[
B_1 = \{ x_a \in C[0,1] \times \mathbb{R} : |x_a| \leq R_1 \} \quad \text{and} \quad B_2 = \{ y_b \in C[0,1] \times \mathbb{R} : |y_b| \leq R_2 \},
\]
then \( T(B) \subset B \) and Schauder’s fixed point theorem can be applied. \( \square \)

In what follows, we give an application of the Leray-Schauder Principle and we assume that the nonlinearities \( f_1, f_2 \) and also the functionals \( \alpha, \beta \) satisfy more general growth conditions, namely:

\[
\begin{align*}
(f_1(t, x, y)) &\leq \omega_1(t, |x|, |y|), \\
(f_2(t, x, y)) &\leq \omega_2(t, |x|, |y|),
\end{align*}
\]
for all \( x, y \in \mathbb{R} \),

\[
\begin{align*}
(\alpha[x, y]) &\leq \omega_3(|x|, |y|), \\
(\beta[x, y]) &\leq \omega_4(|x|, |y|),
\end{align*}
\]
for all \( x, y \in C[0, 1] \). Here \( \omega_1, \omega_2 \) are \( L^1 \)-Carathéodory functions on \([0,1] \times \mathbb{R}^2 \), nondecreasing in their second and third arguments, and \( \omega_3, \omega_4 \) are continuous functions on \( \mathbb{R}^2 \), nondecreasing in both variables.

**Theorem 3.2.** Assume that the conditions \((3.5), (3.6)\) hold. In addition assume that there exists \( R_0 = (R_0^1, R_0^2) \in (0, \infty)^2 \) such that for \( \rho = (\rho_1, \rho_2) \in (0, \infty)^2 \)

\[
\int_0^1 \omega_1(s, \rho_1, \rho_2) ds + \omega_3(\rho_1, \rho_2) \geq \rho_1
\]

\[
\int_0^1 \omega_2(s, \rho_1, \rho_2) ds + \omega_4(\rho_1, \rho_2) \geq \rho_2
\]

implies \( \rho \leq R_0 \).

Then the problem \((1.1)\) has at least one solution.

**Proof.** The result follows from the Leray-Schauder fixed point theorem once we have proved the boundedness of the set of all solutions to equation \( u = \lambda T(u) \), for \( \lambda \in (0, 1) \). Let \( u = (x_a, y_b) \) be such a solution. Then \( x_a = \lambda T_1(x_a, y_b) \) and \( y_b = \lambda T_2(x_a, y_b) \), or equivalently

\[
\begin{align*}
(x, a) &= \lambda \left( a + \int_0^t f_1 \left( s, x(s), y(s) \right) ds, \alpha[x, y] \right), \\
(y, b) &= \lambda \left( b + \int_0^t f_2 \left( s, x(s), y(s) \right) ds, \beta[x, y] \right).
\end{align*}
\]
First, we obtain that

\[ |x(t)| = \lambda \left| a + \int_0^t f_1(s, x(s), y(s)) \, ds \right| \]

\[ \leq |a| + \int_0^t |f_1(s, x(s), y(s))| \, ds \]

\[ \leq |a| + \int_0^1 \omega_1(s, |x(s)|, |y(s)|) \, ds \]

\[ \leq |a| + \int_0^1 \omega_1(s, \rho_1, \rho_2) \, ds \]

(3.8)

where \( \rho_1 = |x|_C, \rho_2 = |y|_C \). Also

(3.9)

\[ |a| = |\lambda \alpha[x, y]| \leq \omega_3(\rho_1, \rho_2). \]

Similarly, we have that

(3.10)

\[ |y(t)| \leq |b| + \int_0^1 \omega_2(s, \rho_1, \rho_2) \, ds \]

and

(3.11)

\[ |b| \leq \omega_4(\rho_1, \rho_2). \]

Then from (3.8)-(3.11), we deduce

\[
\begin{cases}
\rho_1 \leq \int_0^1 \omega_1(s, \rho_1, \rho_2) \, ds + \omega_3(\rho_1, \rho_2) \\
\rho_2 \leq \int_0^1 \omega_2(s, \rho_1, \rho_2) \, ds + \omega_4(\rho_1, \rho_2).
\end{cases}
\]

This by (3.7) guarantees that

(3.12)

\[ \rho \leq R_0. \]

It follows that

(3.13)

\[ |a| \leq \omega_3(R_0) =: R_1^1, \quad |b| \leq \omega_4(R_0) =: R_1^2. \]

Finally (3.12) and (3.13) show that the solutions \( u = (x_a, y_b) \) are \textit{a priori} bounded independently on \( \lambda \). Thus Leray-Schauder’s fixed point theorem can be applied.

\[ \square \]

4. Numerical examples

In what follows, we give two numerical examples that illustrate our theory.
Example 4.1. Consider the nonlocal problem
\[
\begin{align*}
    x' &= \frac{1}{4} \sin x + ay + g(t) \equiv f_1(t, x, y), \\
    y' &= \cos (ax + \frac{1}{4}y) + h(t) \equiv f_2(t, x, y), \\
    x(0) &= \frac{1}{8} \sin (x \left(\frac{1}{4}\right) + y \left(\frac{1}{4}\right)), \\
    y(0) &= \frac{1}{8} \cos (x \left(\frac{1}{4}\right) + y \left(\frac{1}{4}\right)),
\end{align*}
\]
where \( t \in [0, 1], \ a \in \mathbb{R} \) and \( g, h \in L^1(0, 1) \). We have \( a_1 = 1/4, \ b_1 = |a|, \ a_2 = |a|, \ b_2 = 1/4 \) and \( A_1 = B_1 = A_2 = B_2 = 1/8 \). Consider \( \theta = 2 \). Hence
\[
M_\theta = \begin{bmatrix}
    \frac{1}{2} & |a| + \frac{1}{4} \\
    |a| + \frac{1}{4} & \frac{1}{2}
\end{bmatrix}.
\]
Since the eigenvalues of \( M_\theta \) are \( \lambda_1 = -|a| + \frac{3}{4}, \ \lambda_2 = |a| + \frac{3}{4} \), the matrix (4.2) is convergent to zero if \( |\lambda_1| < 1 \) and \( |\lambda_2| < 1 \). It is also known that a matrix of this type is convergent to zero if \( |a| + \frac{1}{4} + \frac{1}{2} < 1 \) (see [46]). Therefore, if \( |a| < \frac{1}{6} \), the matrix (4.2) is convergent to zero and from Theorem 2.1 the problem (4.1) has a unique solution.

Example 4.2. Consider the nonlocal problem
\[
\begin{align*}
    x' &= \frac{1}{4} x \sin \left(\frac{y}{x}\right) + ay \sin \left(\frac{x}{y}\right) + g(t) \equiv f_1(t, x, y), \\
    y' &= ax \sin \left(\frac{y}{x}\right) + \frac{1}{4} y \sin \left(\frac{x}{y}\right) + h(t) \equiv f_2(t, x, y), \\
    x(0) &= \frac{1}{8} \sin \left( x \left(\frac{1}{4}\right) + y \left(\frac{1}{4}\right) \right), \\
    y(0) &= \frac{1}{8} \cos \left( x \left(\frac{1}{4}\right) + y \left(\frac{1}{4}\right) \right),
\end{align*}
\]
where \( t \in [0, 1], \ a \in \mathbb{R} \) and \( g, h \in L^1(0, 1) \). Since
\[
|f_1(t, x, y)| \leq \frac{1}{4} |x| + |a| |y| + |g(t)|
\]
\[
|f_2(t, x, y)| \leq |a| |x| + \frac{1}{4} |y| + |h(t)|
\]
we are under the assumptions from the first part of Section 3. Also, the matrix \( M_0 \) is that from Example 4.1 if we consider \( \theta = 2 \). Therefore, according to Theorem 3.1, if that matrix is convergent to zero, then the problem (4.3) has at least one solution. Note that the functions \( f_1(t, x, y), f_2(t, x, y) \) from this example do not satisfy Lipschitz conditions in \( x, y \) and consequently Theorem 2.1 does not apply.

Acknowledgements

This work was possible with the financial support of the Sectoral Operational Programme for Human Resources Development 2007-2013, co-financed by the European Social Fund, under the project number POSDRU/107/1.5/S/76841 with the title ”Modern Doctoral Studies: Internationalization and Interdisciplinarity”, and by a grant of the Romanian National
References


Octavia Bolojan-Nica, Departamentul de Matematică, Universitatea Babeş-Bolyai, Cluj 400084, Romania

_E-mail address:_ octavia.nica@math.ubbcluj.ro

Gennaro Infante, Dipartimento di Matematica ed Informatica, Università della Calabria, 87036 Arcavacata di Rende, Cosenza, Italy

_E-mail address:_ gennaro.infante@unical.it

Radu Precup, Departamentul de Matematică, Universitatea Babeş-Bolyai, Cluj 400084, Romania

_E-mail address:_ r.precup@math.ubbcluj.ro