EXISTENCE AND STABILITY RESULTS FOR FRACTIONAL DIFFERENTIAL EQUATIONS WITH TWO CAPUTO FRACTIONAL DERIVATIVES

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Abstract. In this paper, we discuss the existence, uniqueness and stability of solutions for a nonlocal boundary value problem of nonlinear fractional differential equations with two Caputo fractional derivatives. By applying the contraction mapping and O’Regan fixed point theorem, the existence results are obtained. We also derive the Ulam-Hyers stability of solutions. Finally, some examples are given to illustrate our results.

Keywords: Caputo derivative, Fixed point, Existence, Uniqueness, Boundary value problem.

1. Introduction

Boundary value problems for fractional differential equations with nonlocal boundary conditions constitute a very interesting and important class of problems (see [4, 5]). Differential equations of fractional order with nonlocal boundary conditions arise in a variety of different areas of applied mathematics and physics. For example, heat conduction, chemical engineering, underground water flow, thermo-elasticity, and plasma physics can be reduced to nonlocal problems with integral boundary conditions. For more details, we refer the reader to [6, 25]. Recently, by applying different fixed point theorems such as the Banach fixed point theorem, Schaefer’s fixed point theorem, Krasnoselskii’s fixed point theorem, the Leray-Schauder nonlinear alternative and the fixed point theorem of O’Regan, many researchers have obtained some interesting results of the existence and uniqueness of solutions to boundary value problems for fractional differential equations with nonlocal boundary value problems [1, 2, 7, 8, 9, 14, 15, 18, 23, 24] and the references therein. Ulam’s stability problem [17] has been attracted by several famous researchers. Since then, a large number of monographs have been published in connection with
various generalizations of Ulam’s type stability theory or the Ulam-Hyers stability theory. For some recent development on Ulam’s type stability, we refer the reader to [3, 12, 16, 17, 19, 20, 21, 22]. The stability of fractional differential equations has been investigated by many authors [19, 21, 22].

Motivated by the above papers, we study the existence, uniqueness and stability of solutions to the following fractional boundary value problem with tow Caputo fractional derivatives involving nonlocal boundary conditions:

\begin{equation}
\begin{aligned}
& D^\alpha (D^\beta + \lambda) x (t) = f (t, x (t)) + \int_0^t \frac{(t-s)^{\alpha-1}}{\Gamma(\alpha)} f (s, x (s)) ds, \quad t \in [0, T], \\
& x (0) = x_0 + g (x), \quad x (T) = \theta \int_0^\eta \frac{(\eta-s)^{p-1}}{\Gamma (p)} x (s) ds, \quad 0 < \eta < T,
\end{aligned}
\end{equation}

where $D^\alpha, D^\beta$ denote the Caputo fractional derivatives, with $0 < \alpha, \beta \leq 1.1 < \alpha + \beta \leq 2$, $f : [0, T] \times \mathbb{R} \to \mathbb{R}$ and $g : C ([0, T], \mathbb{R}) \to \mathbb{R}$ are given continuous functions, and $\sigma, p > 0, \lambda, x_0, \theta$ are real constants in (1.1), $g (x)$ may be regarded as $g (x) = \sum_{j=0}^m k_j x (t_j)$, where $k_j, j = 1, \ldots, m$ are given constants and $0 < t_0 < \ldots < t_m \leq 1$.

The paper is organized as follows: In Section 2, we recall some preliminaries and lemmas that we need in the sequel. In Section 3, we present our main results for the existence, uniqueness and stability of solutions to the fractional boundary value problem (1.1). Some examples to illustrate our results are presented in Section 4.

2. Preliminaries

In this section, we present some useful definitions and lemmas [10, 11, 13]:

**Definition 2.1.** The Riemann-Liouville fractional integral operator of order $\vartheta \geq 0$, for a continuous function $f$ on $[a, b]$ is defined as:

\[ I^\vartheta f (t) = \frac{1}{\Gamma (\vartheta)} \int_a^t (t - \tau)^{\vartheta-1} f (\tau) d\tau, \quad \vartheta > 0, \quad a \leq t \leq b \]

\[ I^0 f (t) = f (t), \]

where $\Gamma (\vartheta) := \int_0^{+\infty} e^{-u} u^{\vartheta-1} du$.

**Definition 2.2.** The fractional derivative of $f \in C^n ([a, b])$ in Caputo’s sense is defined as:

\[ D^\vartheta f (t) = \frac{1}{\Gamma (n-\vartheta)} \int_a^t (t - \tau)^{n-\vartheta-1} f^{(n)} (\tau) d\tau, \quad n - 1 < \vartheta, \quad n \in \mathbb{N}^*, \quad a \leq t \leq b. \]
The following lemmas give some properties of Riemann-Liouville fractional integrals and the Caputo fractional derivative [10, 11]:

**Lemma 2.1.** Let \( \vartheta, s > 0, f \in L^1([a, b]) \). Then \( I^{\vartheta} I^s f(t) = I^{\vartheta+s} f(t), D^s I^s f(t) = f(t), t \in [a, b] \).

**Lemma 2.2.** Let \( s > \theta > 0, f \in L^1([a, b]) \). Then \( D^\theta I^s f(t) = I^{s-\theta} f(t), t \in [a, b] \).

We also give the following lemmas [10]:

**Lemma 2.3.** For \( \vartheta > 0 \), the general solution to the fractional differential equation \( D^\vartheta x(t) = 0 \) is given by

\[
    x(t) = c_0 + c_1 t + c_2 t^2 + \ldots + c_n t^{n-1},
\]

where \( c_i \in \mathbb{R}, i = 0, 1, 2, \ldots, n-1, n = [\vartheta]+1 \).

**Lemma 2.4.** Let \( \vartheta > 0 \). Then

\[
    I^\vartheta D^\vartheta x(t) = x(t) + c_0 + c_1 t + c_2 t^2 + \ldots + c_n t^{n-1},
\]

for some \( c_i \in \mathbb{R}, i = 0, 1, 2, \ldots, n-1, n = [\vartheta]+1 \).

We also need the following auxiliary result:

**Lemma 2.5.** For a given \( h \in C([0, T], \mathbb{R}) \), the solution to the fractional boundary value problem

\[
\begin{align*}
    D^\alpha (D^\beta + \lambda) x(t) &= h(t), \quad t \in [0, T], \quad 0 < \alpha, \beta \leq 1, \\
    x(0) &= x_0 + g(x), \quad x(T) = \theta I^p x(\eta),
\end{align*}
\]

is given by

\[
\begin{align*}
    x(t) &= \int_0^t \frac{(t-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} h(s) \, ds - \lambda \int_0^t \frac{(t-s)^{\beta-1}}{\Gamma(\beta)} x(s) \, ds \\
    &\quad - \frac{\Delta t^\beta}{\Gamma(\beta+1)} \int_0^T \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} h(s) \, ds + \frac{\lambda \Delta t^\beta}{\Gamma(\beta+1)} \int_0^T \frac{(T-s)^{\beta-1}}{\Gamma(\beta)} x(s) \, ds \\
    &\quad + \frac{\Delta \theta t^\beta}{\Gamma(\beta+1)} \int_0^\eta \frac{(\eta-s)^{\alpha+\beta+p-1}}{\Gamma(\alpha+\beta+p)} h(s) \, ds - \frac{\lambda \Delta \theta t^\beta}{\Gamma(\beta+1)} \int_0^\eta \frac{\eta-s)^{\beta+p-1}}{\Gamma(\beta+p)} x(s) \, ds \\
    &\quad + \left( \frac{\theta \eta^p - \Gamma(p+1)}{\Gamma(p+1) \Gamma(\beta+1)} + 1 \right) (x_0 + g(x)),
\end{align*}
\]

where

\[
\Delta = \frac{\Gamma(\beta+p+1) \Gamma(\beta+1)}{\Gamma(\beta+p+1) \Gamma(\beta+1) \theta \eta^{\beta+p}}, \quad \Gamma(\beta+p+1) T^\beta \neq \Gamma(\beta+1) \theta \eta^{\beta+p}.
\]
Proof. By Lemmas 5 and 6, we have
\[ x(t) = I^{\alpha+\beta} h(t) - \lambda I^\beta x(t) - \frac{c_0}{\Gamma(\beta + 1)} t^\beta - c_1, \]
for some arbitrary constants \( c_0, c_1 \in \mathbb{R} \).

Using the boundary condition: \( x(0) = x_0 + g(x) \), we obtain
\[ c_1 = -(x_0 + g(x)). \]

Thanks to Lemma 3, we get
\[ I^p x(t) = I^{\alpha+\beta+p} h(t) - \lambda I^\beta x(t) - \frac{c_0}{\Gamma(\beta + p + 1)} (p+\beta - \frac{c_1}{\Gamma(p+1)} p. \]

Applying the boundary condition: \( x(T) = \theta I^p x(\eta) \), we obtain
\[ c_0 = \Delta \left[ (I^{\alpha+\beta} h(T) - \lambda I^\beta x(T) - \theta I^{\alpha+\beta+p} h(\eta) + \lambda \theta I^\beta x(\eta) - \frac{(\theta p-\Gamma(p+1))}{\Gamma(p+1)} (x_0 + g(x)) \right], \]
where \( \Delta \) defined by (2.3). Substituting the value of \( c_0 \) and \( c_1 \) in (2.4), we obtain the solution (2.2). \( \square \)

In view of Lemma 4, we define the operator: \( \phi : X \rightarrow X \) as
\[ (2.5) \phi x(t) = \int_0^t (t-s)^{\alpha+\beta-1} f(s, x(s)) ds - \lambda \int_0^t \frac{(t-s)^{\beta-1}}{\Gamma(\beta)} x(s) ds \]
\[ - \frac{\Delta t^\beta}{\Gamma(\beta + 1)} \int_0^T \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} f(s, x(s)) ds + \frac{\lambda \Delta t^\beta}{\Gamma(\beta)} \int_0^T \frac{(T-s)^{\beta-1}}{\Gamma(\beta)} x(s) ds \]
\[ + \frac{\Delta \theta t^\beta}{\Gamma(\beta + 1)} \int_0^\eta \frac{(\eta-s)^{\alpha+\beta+p-1}}{\Gamma(\alpha+\beta+p)} f(s, x(s)) ds - \frac{\lambda \Delta \theta t^\beta}{\Gamma(\beta)} \int_0^\eta \frac{(\eta-s)^{\beta+p-1}}{\Gamma(\beta+p)} x(s) ds \]
\[ + \left( \frac{\Delta (\theta p-\Gamma(p+1))}{\Gamma(p+1)} t^\beta + 1 \right) (x_0 + g(x)), \]

We also introduce the operators \( \phi_1, \phi_2 : X \rightarrow X \), such that
\[ (2.6) \phi_1 x(t) = \int_0^t (t-s)^{\alpha+\beta-1} f(s, x(s)) ds - \lambda \int_0^t \frac{(t-s)^{\beta-1}}{\Gamma(\beta)} x(s) ds \]
\[ - \frac{\Delta t^\beta}{\Gamma(\beta + 1)} \int_0^T \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} f(s, x(s)) ds + \frac{\lambda \Delta t^\beta}{\Gamma(\beta)} \int_0^T \frac{(T-s)^{\beta-1}}{\Gamma(\beta)} x(s) ds \]
\[ + \frac{\Delta \theta t^\beta}{\Gamma(\beta + 1)} \int_0^\eta \frac{(\eta-s)^{\alpha+\beta+p-1}}{\Gamma(\alpha+\beta+p)} f(s, x(s)) ds - \frac{\lambda \Delta \theta t^\beta}{\Gamma(\beta)} \int_0^\eta \frac{(\eta-s)^{\beta+p-1}}{\Gamma(\beta+p)} x(s) ds, \]
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and

\begin{equation}
\phi_2(x) (t) = \left( \frac{\theta p - \Gamma (p + 1)}{\Gamma (p + 1)} t^\beta + 1 \right) (x_0 + g(x)).
\end{equation}

Clearly

\begin{equation}
\phi(x) (t) = \phi_1(x) (t) + \phi_2(x) (t), \ t \in [0, T].
\end{equation}

3. Main Results

We denote by \( X = C([0, T], \mathbb{R}) \) the Banach space of all continuous functions from \([0, T]\) into \( \mathbb{R}\) endowed with a topology of uniform convergence with the norm defined by \( \|x\| = \sup \{|x(t)| : t \in [0, T]\} \).

For computational convenience, we set the notations:

\begin{equation}
\Lambda = \frac{T^{\alpha+\beta}}{\Gamma (\alpha + \beta + 1)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma (\alpha + \beta + \sigma + 1)} + \frac{|\Delta| T^\beta}{\Gamma (\beta + 1)} \left[ \frac{T^{\alpha+\beta}}{\Gamma (\alpha + \beta + 1)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma (\alpha + \beta + \sigma + 1)} + \frac{|\theta| \eta^{\alpha+\beta+p}}{\Gamma (\alpha + \beta + p + 1)} + \frac{|\theta| \eta^{\alpha+\beta+p+\sigma}}{\Gamma (\alpha + \beta + p + \sigma + 1)} \right],
\end{equation}

\begin{equation}
\Lambda_1 = \frac{|\Delta| (\theta p^\beta - \Gamma (p + 1)) T^\beta}{\Gamma (p + 1) \Gamma (\beta + 1)} + 1,
\end{equation}

\begin{equation}
\Lambda_2 = \frac{|\lambda| T^\beta}{\Gamma (\beta + 1)} \left[ 1 + \frac{|\Delta| T^\beta}{\Gamma (\beta + 1)} + \frac{|\Delta p| \eta^{\beta+p}}{\Gamma (\beta + p + 1)} \right],
\end{equation}

and

\begin{equation}
\rho = \left[ \frac{T^{\alpha+\beta}}{\Gamma (\alpha + \beta + 1)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma (\alpha + \beta + \sigma + 1)} + \frac{|\Delta| T^\beta}{\Gamma (\beta + 1)} \left( \frac{T^{\alpha+\beta}}{\Gamma (\alpha + \beta + 1)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma (\alpha + \beta + \sigma + 1)} + \frac{|\theta| \eta^{\alpha+\beta+p}}{\Gamma (\alpha + \beta + p + 1)} + \frac{|\theta| \eta^{\alpha+\beta+p+\sigma}}{\Gamma (\alpha + \beta + p + \sigma + 1)} \right) \right] \|\gamma\|.
\end{equation}

Now, we impose the following hypotheses:

\((H1)\) : There exists a constant \( \omega > 0 \) such that for all \( t \in [0, T] \) and \( x, y \in C ([0, T], \mathbb{R}) \), we have \( |f(t, x) - f(t, y)| \leq \omega \|x - y\| \),
(H2) : There exists a positive constant $\varpi < \frac{1}{\Lambda_1}$ and a continuous function $\varphi : [0, \infty) \to [0, \infty)$ such that $\varphi(u) \leq \varpi u$ and $|g(x) - g(y)| \leq \varpi(\|x - y\|)$, for all $x, y \in C([0, T])$.

(H3) : $g(0) = 0$.

(H4) : There exists a non-negative function $\gamma (t) \in C([0, T], \mathbb{R})$ and there exists a nondecreasing function $\psi : [0, \infty) \to (0, \infty)$, such that $|f(t, x)| \leq \gamma(t) \psi(|x|)$ for all $(t, x) \in [0, T] \times X$.

(H5) : \[
\sup_{r \in (0, \infty)} \frac{r}{\rho \psi(r) + \Lambda_1 |x_0|} > \frac{1}{1 - (\Lambda_2 + \Lambda_1 \varpi)}, \]
where $\Lambda_1$, $\rho$ and $\Lambda_2$ are given respectively in (3.2), (3.3) and (3.4).

3.1. Existence and uniqueness of solutions

The first result is concerned with the existence and uniqueness of solutions to fractional boundary value problems and is based on the Banach contraction principle.

**Theorem 3.1.** Let $f : [0, T] \times \mathbb{R} \to \mathbb{R}$ be a continuous function. Assume that (H1) and (H2) hold. If the inequality

\[
\Lambda \omega + \Lambda_1 \varpi < 1 - \Lambda_2,
\]

is valid, then the fractional boundary value problem (1.1) has a unique solution on $[0, T]$.

**Proof.** For $x, y \in X$ and by (H1) and (H2) we have:

\[
\|\phi(x) - \phi(y)\| \leq \sup_{t \in [0, T]} \left\{ \int_0^t \frac{(t-s)^{\alpha - 1}}{\Gamma(\alpha)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ \int_0^t \frac{(t-s)^{\beta - 1}}{\Gamma(\beta)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ |\lambda| \int_0^t \frac{(t-s)^{\gamma - 1}}{\Gamma(\gamma)} |x(s) - y(s)| \, ds \\
+ \frac{|\Delta| \varphi}{\Gamma(\gamma + 1)} \int_0^T \frac{(T-s)^{\alpha - 1}}{\Gamma(\alpha)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ \frac{|\Delta| \varphi}{\Gamma(\gamma + 1)} \int_0^T \frac{(T-s)^{\beta - 1}}{\Gamma(\beta)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ |\lambda| |\Delta| \varphi \int_0^T \frac{(T-s)^{\gamma - 1}}{\Gamma(\gamma)} |x(s) - y(s)| \, ds \\
+ \frac{|\Delta| \varphi}{\Gamma(\gamma + 1)} \int_0^T \frac{(T-s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta + 1)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ \frac{|\Delta| \varphi}{\Gamma(\gamma + 1)} \int_0^T \frac{(T-s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta + 1)} |f(s, x(s)) - f(s, y(s))| \, ds \\
+ |\lambda| |\Delta| \varphi \int_0^T \frac{(T-s)^{\gamma + \beta - 1}}{\Gamma(\gamma + \beta + 1)} |x(s) - y(s)| \, ds \\
+ \frac{|\Delta| \varphi}{\Gamma(\gamma + 1)} \int_0^T \frac{(T-s)^{\alpha + \beta + \gamma - 1}}{\Gamma(\alpha + \beta + \gamma + 1)} |f(s, x(s)) - f(s, y(s))| \, ds \right\}
\]
a nonnegative nondecreasing function \( \varphi \) represents the closure (respectively the boundary) of \( V \).

In the next result, we prove the existence of solutions to the fractional boundary value problem by applying the following Lemma.

**Lemma 3.1.** (O’Regan Lemma) [15]. Denote by \( V \) an open set in a closed, convex set \( C \) of a Banach space \( E \). Assume \( 0 \in V \). Also assume that \( \varphi (\bar{V}) \) is bounded and that \( \varphi : \bar{V} \rightarrow C \) is given by \( \varphi = \varphi_1 + \varphi_2 \), in which \( \varphi_1 : \bar{V} \rightarrow E \) is continuous and completely continuous and \( \varphi_2 : \bar{V} \rightarrow E \) is a nonlinear contraction (i.e., there exists a nonnegative nondecreasing function \( \varphi : (0, \infty) \rightarrow (0, \infty) \) satisfying \( \varphi (u) < u \) for \( v > 0 \) such that \( \| \varphi_2 (x) - \varphi_2 (y) \| \leq \varphi \| x - y \| \) for all \( x, y \in \bar{V} \)). Then, either

(I) : \( \varphi \) has a fixed point \( x \in \bar{V} \); or

(II) : there exists a point \( x \in \partial V \) and \( 0 < \mu < 1 \) with \( x = \mu \varphi (x) \), where \( \bar{V} \) (respectively \( \partial V \)) represents the closure (respectively the boundary) of \( V \).

Thanks to (3.5), we conclude that \( \varphi \) is a contraction. As a consequence of the Banach fixed point theorem, we deduce that \( \varphi \) has a fixed point which is a solution to the fractional boundary value problem (1.1). \( \square \)
Let
\[ \Omega := \{ x \in C([0,T], \mathbb{R}) : \| x \| < \delta \}, \]
and denote the maximum number by
\[ N_b := \max \{|f(t,x)| : (t,x) \in [0,T] \times [\delta, -\delta]\}. \]

**Theorem 3.2.** Let \( f : [0,T] \times \mathbb{R} \to \mathbb{R} \) be a continuous function. Suppose that \((H2),(H3),(H4)\) and \((H5)\) are satisfied.

Then the boundary value problem (1.1) has at least one solution on \([0,T]\).

**Proof.** Consider the operator \( \phi : X \to X \) defined by:
\[ \phi(x)(t) := \phi_1(x)(t) + \phi_2(x)(t) , \quad t \in [0,T], \]
where the operators \( \phi_1 \) and \( \phi_2 \) are defined respectively in (2.6) and (2.7).

From \((H5)\) there exists a number \( \delta_0 > 0 \) such that
\[ (3.6) \]
\[ \frac{\delta_0}{\rho \psi(\delta_0) + \Lambda_1 \| x_0 \|} \geq \frac{1}{\Gamma(\Lambda_2 + \Lambda_1 \varepsilon)}. \]

We shall prove that the operators \( \phi_1 \) and \( \phi_2 \) satisfy all the conditions in Lemma 9.

**Step 1:** We show that the operator \( \phi_1 : \Omega_{b} \to X \) is continuous and completely continuous. Let us consider the set
\[ (3.7) \]
\[ \overline{\Omega}_{b} := \{ x \in C([0,T], \mathbb{R}) : \| x \| \leq \delta_0 \}, \]
and show that \( \phi_1(\overline{\Omega}_{b}) \) is bounded. For each \( x \in \overline{\Omega}_{b} \), we have
\[
\| \phi_1(x) \| \\
\leq \sup_{t \in [0,T]} \left\{ \int_{0}^{t} \frac{(t-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} |f(s,x(s))| ds + \int_{0}^{t} \frac{(t-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma)} |f(s,x(s))| ds \\
+ |\lambda| \int_{0}^{T} \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\beta)} |x(s)| ds + |\lambda| \int_{0}^{\gamma} \frac{(\gamma-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\beta+\sigma)} |x(s)| ds + |\theta| \int_{0}^{\eta} \frac{(\eta-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\beta+\sigma+p)} |f(s,x(s))| ds + |\theta| \int_{0}^{\gamma} \frac{(\gamma-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\beta+\sigma+p)} |f(s,x(s))| ds \\
+ |\lambda| \int_{0}^{\gamma} \frac{(\gamma-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\beta+\sigma+p)} |x(s)| ds \right\} \\
\leq \left( \frac{T^{\alpha+\beta}}{\Gamma(\alpha+\beta+\sigma)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma(\alpha+\beta+\sigma+p)} + \frac{\Delta T^{\beta}}{\Gamma(\beta+\eta)} \left( \frac{T^{\alpha+\beta}}{\Gamma(\alpha+\beta+\sigma)} + \frac{T^{\alpha+\beta+\sigma}}{\Gamma(\alpha+\beta+\sigma+p)} + \frac{\Delta T^{\beta}}{\Gamma(\beta+\sigma+p)} \right) N_b \| \gamma \| \\
+ \frac{|\lambda| T^{\beta}}{\Gamma(\beta+\eta)} \left( 1 + \frac{\Delta T^{\beta}}{\Gamma(\beta+\eta)} + \frac{\Delta T^{\beta}}{\Gamma(\beta+\sigma+p)} \right) \delta_0 \right) \\
= \Lambda N_b \| \gamma \| + \Lambda_2 \delta_0.
\]
Thus the operator $\phi_1(\overline{\Omega_{\beta_0}})$ is uniformly bounded. For any $0 \leq t_1 < t_2 \leq T$, we have

$$
|\phi_1(x(t_2) - \phi_1(x(t_1))| \leq \int_0^{t_1} \left[ (t_2 - s)^{\alpha + \beta - 1} \phi_1(x(s)) \right] ds + \int_0^{t_1} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |f(s, x(s))| ds + \int_0^{t_1} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |f(s, x(s))| ds
$$

$$
+ |\lambda| \left[ \int_0^{t_1} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |x(s)| ds + |\lambda| \int_0^{t_1} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |x(s)| ds
$$

$$
+ |\Delta \lambda| \int_0^{T} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |x(s)| ds + |\Delta \lambda| \int_0^{T} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta)} |x(s)| ds
$$

$$
+ |\Delta \lambda| \int_0^{T} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta + p + \sigma)} |f(s, x(s))| ds + |\Delta \lambda| \int_0^{T} \frac{(t_2 - s)^{\alpha + \beta - 1}}{\Gamma(\alpha + \beta + p + \sigma)} |f(s, x(s))| ds
$$

$$
\leq \frac{N_{\beta_0} \| \gamma \|}{\Gamma(\alpha + \beta + 1)} \left| t_2^{\alpha + \beta} - t_1^{\alpha + \beta} \right| + \frac{N_{\beta_0} \| \gamma \|}{\Gamma(\alpha + \beta + 1)} \left| t_2^{\alpha + \beta + \sigma} - t_1^{\alpha + \beta + \sigma} \right|
$$

$$
+ \left[ |\Delta \lambda| \frac{N_{\beta_0} \| \gamma \|}{\Gamma(\alpha + \beta + 1)} \left( \frac{T^{\alpha + \beta}}{\Gamma(\alpha + \beta + 1)} + \frac{T^{\alpha + \beta + \sigma}}{\Gamma(\alpha + \beta + 1)} \right) + \frac{|\lambda| \delta_0}{\Gamma(\alpha + \beta + p + \sigma)} \right]
$$

$$
+ \left[ |\Delta \lambda| \frac{T^{\alpha + \beta}}{\Gamma(\alpha + \beta + 1)} + \frac{|\lambda| \delta_0}{\Gamma(\alpha + \beta + p + \sigma)} \right] \left| t_2^2 - t_1^2 \right|
$$

which is independent of $x$ and tends to zero as $t_2 \to t_1$. Thus, $\phi_1$ is equicontinuous. Hence, by the Arzela–Ascoli theorem, $\phi_1(\overline{\Omega_{\beta_0}})$ is a relatively compact set. Now, let the sequence $x_n \subset \overline{\Omega_{\beta_0}}$ with $x_n \to x$. Then $x_n(t) \to x(t)$ uniformly valid on $[0, T]$, then for each $t \in [0, T]$, we have. From the uniform continuity of $f(t, x(t))$ on the compact set $[0, T] \times \overline{\Omega_{\beta_0}}$, it follows that $\|f(t, x_n(t)) - f(t, x(t))\| \to 0$ is uniformly valid on $J$. Hence $\|f_1(x_n(t)) - f_1(x(t))\| \to 0$ as $n \to \infty$, which proves the continuity of $\phi_1(\overline{\Omega_{\beta_0}})$.

**Step 2**: The operator $\phi_2 : \overline{\Omega_{\beta_0}} \to X$ is contractive, this is the consequence of (H2).

**Step 3**: The set $\phi_2(\overline{\Omega_{\beta_0}})$ is bounded. For any $x \in \overline{\Omega_{\beta_0}}$ and by (H2) and (H3), we have

$$
||\phi_2(x)|| \leq \Lambda_1 (|x_0| + \omega \delta_0),
$$

combining, with the set $\phi_1(\overline{\Omega_{\beta_0}})$ being bounded, then the set $\phi(\overline{\Omega_{\beta_0}})$ is bounded.

**Step 4**: Finally, we will show that the case (II) in Lemma 9 does not hold. On the contrary, we suppose that (II) holds. Then, there exist $\mu \in (0, 1)$ and $x \in \partial \Omega_{\beta_0}$,
such that $x = \mu \phi(x)$. So we have $\|x\| = \delta_0$ and

$$x(t) = \mu \left[ \int_0^t \frac{(t-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} f(s, x(s)) ds + \int_0^t \frac{(t-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma)} f(s, x(s)) ds \right]$$

$$- \lambda \int_0^T \frac{(T-s)^{\beta-1}}{\Gamma(\beta)} x(s) ds - \Delta \int_0^T \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} f(s, x(s)) ds$$

$$+ \lambda \Delta \int_0^T \frac{(T-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma)} f(s, x(s)) ds + \lambda \Delta \int_0^T (T-s)^{\alpha+\beta+\sigma-1} x(s) ds$$

$$- \lambda \Delta \int_0^T (T-s)^{\alpha+\beta+\sigma-1} f(s, x(s)) ds + \lambda \Delta \int_0^T (T-s)^{\alpha+\beta+\sigma-1} (x(s) + g(x)) ds , \quad t \in [0, T].$$

Using the hypotheses $(H3) - (H5)$ we get

$$\|x\| \leq \left[ \int_0^t \frac{(t-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} \gamma(s) ds + \int_0^t \frac{(t-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma)} \gamma(s) ds \right]$$

$$+ \left| \Delta \right| t^\beta \int_0^T \frac{(T-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta)} \gamma(s) ds$$

$$+ \left| \Delta \right| t^\beta \int_0^T \frac{(T-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma)} \gamma(s) ds$$

$$+ \lambda \left[ \int_0^t \frac{(t-s)^{\alpha+\beta-1}}{\Gamma(\alpha+\beta+\sigma)} \gamma(s) ds \right] \psi(\|x\|)$$

$$+ \left| \lambda \right| \left[ \int_0^t \frac{(t-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma+1)} ds + \int_0^T \frac{(T-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma+1)} ds \right]$$

$$+ \int_0^T \frac{(T-s)^{\alpha+\beta+\sigma-1}}{\Gamma(\alpha+\beta+\sigma+1)} ds \|x\|$$

$$+ \left( \left| \Delta \right| T^\beta - \frac{\Delta}{\Gamma(p+1)(\alpha+\beta+\sigma+1)} \right) + \left( \left| \Delta \right| (T^\sigma - \frac{\Delta}{\Gamma(p+1)(\alpha+\beta+\sigma+1)}) \right) \|x\|$$

By $(3.3)$ and $(3.7)$, we obtain

$$\delta_0 \leq \left[ \int_0^T \frac{T^{\alpha+\beta}}{\Gamma(\alpha+\beta+\sigma+1)} + \int_0^T \frac{T^{\alpha+\beta+\sigma}}{\Gamma(\alpha+\beta+\sigma+1)} + \left( \left| \Delta \right| T^\beta - \frac{\Delta}{\Gamma(p+1)(\alpha+\beta+\sigma+1)} \right) \right] \|x\|$$

$$+ \left( \left| \lambda \right| T^\beta \left( 1 + \left| \Delta \right| T^\beta + \left| \Delta \right| \frac{T^\sigma}{\Gamma(p+1)(\alpha+\beta+\sigma+1)} + \left( \left| \Delta \right| (T^\sigma - \frac{\Delta}{\Gamma(p+1)(\alpha+\beta+\sigma+1)}) \right) \right) \|x\|$$

$$+ \left( \left| \lambda \right| T^\beta \left( 1 + \left| \Delta \right| T^\beta + \left| \Delta \right| \frac{T^\sigma}{\Gamma(p+1)(\alpha+\beta+\sigma+1)} + \left( \left| \Delta \right| (T^\sigma - \frac{\Delta}{\Gamma(p+1)(\alpha+\beta+\sigma+1)}) \right) \right) \|x\|.$$
which implies
\[ \delta_0 \leq \rho \psi(\delta_0) + (\Lambda_2 + \Lambda_1 \varpi) \delta_0 + \Lambda_1 |x_0|. \]

However,
\[ \frac{\delta_0}{\rho \psi(\delta_0) + \Lambda_1 |x_0|} \leq \frac{1}{1 - (\Lambda_2 + \Lambda_1 \varpi)}, \]
which contradicts (3.6). Consequently, the operators \( \phi_1 \) and \( \phi_2 \) satisfy all the conditions in Lemma 9. Hence, the operator \( \phi \) has at least one fixed point \( x \in \Omega_{\delta_0} \), which is the solution of the fractional boundary value problem (1.1). This completes the proof. \( \square \)

### 3.2. Ulam-Hyers stability

In this section, we will study Ulam’s type stability of the fractional boundary value problem (1.1).

Let \( \varepsilon > 0 \), we consider the equation
\[
D^\alpha (D^\beta + \lambda) x(t) = f(t, x(t)) + \int_0^t \frac{(t-s)^{\alpha-1}}{\Gamma(\alpha)} f(s, x(s)) \, ds
\]
and the following inequality
\[
(3.8) \quad \left| D^\alpha (D^\beta + \lambda) y(t) - f(t, y(t)) + \int_0^t \frac{(t-s)^{\alpha-1}}{\Gamma(\alpha)} f(s, y(s)) \, ds \right| \leq \varepsilon, \quad t \in [0, T],
\]
with \( y(0) = y_0 + g(y), \ y(T) = \theta I^\gamma y(\eta). \)

**Definition 3.1.** The fractional boundary value problem (1.1) is Ulam-Hyers stable if there exists a real number \( k > 0 \) such that for each solution \( y \in X \) to the inequality (3.8) there exists a solution \( x \in X \) of the fractional boundary value problem (1.1) with
\[ \|x - y\| \leq k\varepsilon. \]

**Definition 3.2.** The fractional boundary value problem (1.1) is generalized Ulam-Hyers stable if there exists \( z \in C(\mathbb{R}^+, \mathbb{R}^+) \), \( z(0) = 0 \) such that for each solution \( y \in X \) to the inequality (3.8), there exists a solution \( x \in X \) of the fractional boundary value problem (1.1) with
\[ \|x - y\| \leq z(\varepsilon). \]

**Theorem 3.3.** Let \( f : [0, T] \times \mathbb{R} \to \mathbb{R} \) be a continuous function. Suppose that \((H_1) - (H_4)\) holds. In addition, we assume that:
\[
(H_6) \quad \sup_{t \in [0, T]} |D^\alpha (D^\beta + \lambda) x(t)| \geq \Lambda N_\gamma \|y\| + (\Lambda_2 + \Lambda_1 \varpi) \delta_0 + \Lambda_1 |x_0|.
\]

If
\[
(3.9) \quad \omega < \frac{\Gamma(\sigma + 1)}{[\Gamma(\sigma + 1) + T^\sigma]},
\]
then the fractional boundary value problem (1.1) has the Ulam-Hyers stability in \( X \).
Proof. For each $\varepsilon > 0$, $y \in X$, we have
\[
\left| D^\alpha (D^\beta + \lambda) y(t) - f(t, y(t)) - \int_0^t \frac{(t-s)^{\sigma-1}}{\Gamma(\sigma)} f(s, y(s)) \, ds \right| \leq \varepsilon,
\]
with $y(0) = y_0 + g(y)$, $y(T) = \theta I_p y(\eta)$.

Let us denote by $x \in X$ the unique solution of the fractional boundary value problem (1.1).

According to the assumptions of Theorem 8, we have
\[
|x(t)| \leq \Lambda N_{\beta, \| \gamma \|} + (\Lambda_2 + \Lambda_1 \omega) \delta_0 + \Lambda_1 |x_0|, \quad t \in [0, T].
\]

By $(H_6)$, we get
\[
\sup_{t \in [0, T]} |x(t)| \leq \sup_{t \in [0, T]} \left| D^\alpha (D^\beta + \lambda) x(t) \right|.
\]

Then
\[
\sup_{t \in [0, T]} |x(t) - y(t)| \leq \sup_{t \in [0, T]} \left| D^\alpha (D^\beta + \lambda) (x(t) - y(t)) \right|
\]
\[
\leq \sup_{t \in [0, T]} \left| D^\alpha (D^\beta + \lambda) x(t) - f(t, x(t)) - \int_0^t \frac{(t-s)^{\sigma-1}}{\Gamma(\sigma)} f(s, x(s)) \, ds \right|
\]
\[
- D^\alpha (D^\beta + \lambda) y(t) + f(t, y(t)) + \int_0^t \frac{(t-s)^{\sigma-1}}{\Gamma(\sigma)} f(s, y(s)) \, ds
\]
\[
+ f(t, x(t)) + \int_0^t \frac{(t-s)^{\sigma-1}}{\Gamma(\sigma)} f(s, x(s)) \, ds
\]
\[
- f(t, y(t)) - \int_0^t \frac{(t-s)^{\sigma-1}}{\Gamma(\sigma)} f(s, y(s)) \, ds \right| \leq 2\varepsilon + \left( 1 + \frac{T^\sigma}{\Gamma(\sigma+1)} \right) \omega \sup_{t \in [0, T]} |x(t) - y(t)|.
\]

Hence
\[
\|x - y\| \leq \frac{2 \varepsilon}{1 - \left( 1 + \frac{T^\sigma}{\Gamma(\sigma+1)} \right) \omega} = k \varepsilon.
\]

Thus, the fractional boundary value problem (1.1) has the Ulam-Hyers stability in $X$. $\square$

Remark 3.1. By putting $z(\varepsilon) = k \varepsilon, z(\varepsilon) = 0$ yields that the fractional boundary value problem (1.1) has the generalized Ulam-Hyers stability in $X$.

4. Examples

To illustrate our main results, we treat the following examples.
Example 4.1. Let us consider the following fractional boundary value problem:

\[
\begin{align*}
D_t^\alpha \left( D_t^\beta + \frac{3}{20} \right) x(t) &= \left( \frac{e^{-\tau t} x(t)}{25 \sqrt{\pi e^{-\tau t}}} \right) + \frac{1}{2} + \cosh \left( t^2 + 2 \right) \\
+ \int_0^t \frac{e^{-\tau t} x(s)}{5 + \frac{3}{20}} ds, & \quad t \in [0, 1],
\end{align*}
\]

(4.1)

with \( \alpha = \frac{3}{5}, \beta = \frac{3}{5}, \lambda = \frac{1}{10}, \sigma = \frac{5}{10}, \theta = \frac{5}{10}, \pi = \frac{5}{10}, \eta = \frac{5}{10} \) and

\[ f(t, x) = \frac{e^{-\tau t} x(t)}{25 \sqrt{\pi e^{-\tau t}}} + \frac{1}{2} + \cosh \left( t^2 + 2 \right) \cdot g(x) = \frac{3}{5} x(\zeta). \]

Let \( x, y \in \mathbb{R} \) and \( t \in [0, 1] \). Then

\[ |f(t, x) - f(t, y)| \leq \frac{e^{-\tau t}}{25 \sqrt{\pi e^{-\tau t}}} |x - y| \leq \frac{1}{25 \sqrt{\pi e^{-\tau t}}} |x - y|. \]

Hence the condition \((H_1)\) holds with \( \omega = \frac{1}{25 \sqrt{\pi e^{-\tau t}}} \). Also, for \( x, y \in C[0, 1] \), we have

\[ |g(t, x) - g(t, y)| \leq \frac{1}{19} |x - y|. \]

Therefore, we have

\[ \Delta \omega + \Lambda_1 \omega < 1 - \Lambda_2. \]

Hence, by Theorem 6, the fractional boundary value problem (4.1) has a unique solution on \([0, 1]\).

Example 4.2. Consider the following fractional boundary value problem:

\[
\begin{align*}
D_t^\alpha \left( D_t^\beta + \frac{1}{2} \right) x(t) &= \frac{\text{tanh}(t + e^{\lambda t}) \sqrt{(1 + t) \sin(x^2 - 1)}}{e^{-\lambda t}} \\
+ \int_0^t \frac{\text{tanh}(t + e^{\lambda t}) \sqrt{(1 + t) \sin(x^2 - 1)}}{25 \sqrt{\pi e^{-\lambda t} (|x| + t^2 + 1)}} ds, & \quad t \in [0, 1],
\end{align*}
\]

(4.2)

with \( \alpha = \frac{3}{5}, \beta = \frac{3}{5}, \lambda = \frac{1}{10}, \sigma = \frac{5}{10}, \theta = \frac{5}{10}, \pi = \frac{5}{10}, \eta = \frac{5}{10} \) and \( f(t, x) = \frac{\text{tanh}(t + e^{\lambda t}) \sqrt{(1 + t) \sin(x^2 - 1)}}{25 \sqrt{\pi e^{-\lambda t} (|x| + t^2 + 1)}} \cdot g(x) = \frac{1}{10} x(\xi). \)
For any \( x, y \in C[0, 1] \), we have

\[
|g(x) - g(y)| \leq \frac{\ln 3}{11} \|x - y\| ,
\]

which implies that the function \( g(x) = \frac{\ln x}{x} (\zeta) \) is contractive. Moreover, \( g(0) = 0 \). Hence, the condition \((H_3)\) is satisfied. Also for \( x, y \in [0, 1] \), we have

\[
|f(t, x)| \leq \frac{\tan (t + e^{1-t}) \sqrt{1 + t}}{25e^{\frac{1}{2}t}} (|x| - 1).
\]

So, we take \( \gamma(t) = \frac{\tan (t + e^{1-t}) \sqrt{1 + t}}{25e^{\frac{1}{2}t}}\) and \( \psi(|x|) = |x| + 1 \), then the condition \((H_4)\) is satisfied. With the given values, it is found that

\[
\|\gamma\| = 4.5912 \times 10^{-2},
\]

\[
\rho = \left[ \frac{T^{\alpha + \beta}}{\Gamma(\alpha + \beta + 1)} + \frac{T^{\alpha + \beta + \sigma}}{\Gamma(\alpha + \beta + \sigma + 1)} + \frac{|\Delta|^p}{\Gamma(\alpha + \beta + 1)} \right] \|\gamma\| = 0.93641,
\]

\[
\Lambda = \left[ \frac{T^{\alpha + \beta}}{\Gamma(\alpha + \beta + 1)} + \frac{T^{\alpha + \beta + \sigma}}{\Gamma(\alpha + \beta + \sigma + 1)} + \frac{|\Delta|^p}{\Gamma(\alpha + \beta + 1)} \right] \|\gamma\| = 5.62936,
\]

\[
\Lambda_1 = \left[ \frac{|\Delta|^p}{\Gamma(\alpha + \beta + 1)} \right] \|\gamma\| = 0.12943.
\]

and the condition

\[
\frac{d_{\theta} \|\Delta\|/\|\theta\|}{\Delta \|\theta\|} > \frac{1}{\|\Lambda\|/\|\gamma\|}
\]

implies that \( d_0 > 0.62271 \). Clearly all the conditions of Theorem 10 are satisfied. Hence by the conclusion of Theorem 10, the fractional boundary value problem \((4.2)\) has a solution on \([0, 1]\).

**Example 4.3.** Consider:

\[
D^{rac{\lambda}{2}} \left(D^{rac{\lambda}{2}} + \frac{d}{T} \right) x(t) = \frac{1}{23\ln(t+1+1)} \left( \sinh t + \frac{|x(t)|}{1+|x(t)|} + |x(t)| \right) + 1 + \ln (t + 3)
\]

\[
+ \int_0^t \left( \frac{(t-s)^{\frac{m}{2}}}{T^{\frac{m}{2}}} \right) \left( \sinh t + \frac{|x(s)|}{1+|x(s)|} + |x(s)| \right) + 1 + \ln (s + 3) ds, t \in [0, 1],
\]

\[
x(0) = \sum_{i=1}^n c_i \frac{|x(t_i)|}{1+|x(t_i)|}, \quad x(1) = \sqrt{T} \int_0^T \left( \frac{(t-s)^{\frac{3}{2}}}{T^{\frac{3}{2}}} \right) ds.
\]

where \( 0 < t_1 < t_2 < \ldots < t_n < 1, c_i, i = 1, 2, \ldots, n, \) are given positive constants with

\[
\sum_{i=1}^n c_i < \frac{1}{3}.
\]

Consider the fractional boundary value problem \((4.3)\), with \( \alpha = \frac{3}{2}, \beta = \frac{3}{2}, \lambda = \frac{3}{2}, \sigma = \frac{3}{2}, \theta = \sqrt{T}, p = \frac{3}{2}, \eta = \frac{1}{2} \) and \( f(t, x) = \epsilon e^{-\tau|x(t)|} (1+|x(t)|) + \frac{1}{2} + \cosh (t^2 + 2), \)

\[
g(x) = \sum_{i=1}^n c_i \frac{|x(t_i)|}{1+|x(t_i)|},
\]
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Let \( t \in [0, 1] \) and \( x, y \in \mathbb{R} \). Then

\[
|f(t, x) - f(t, y)| \leq \frac{1}{23 \ln (t + 1) + 1} |x - y| \leq \frac{1}{23} |x - y|.
\]

Hence the condition \((H_1)\) holds with \( \omega = \frac{1}{23} \). Also, for any \( x, y \in C([0, 1]) \), we have

\[
|g(x) - g(y)| \leq \sum_{i=1}^{n} c_i |x - y|.
\]

So, \((H_2)\) is satisfied with \( \rho = \sum_{i=1}^{n} c_i < \frac{1}{2} \).

Thus the condition

\[
\omega = 4.3478 \times 10^{-2} < \frac{\Gamma(\sigma + 1)}{[\Gamma(\sigma + 1) + T^\sigma]} = 0.5435
\]

is satisfied. It follows from Theorem 8 that the fractional boundary value problem (4.3) has a unique solution on \([0, 1]\), and from Theorem 13, the fractional boundary value problem (4.3) has the Ulam-Hyers stability.

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