

# SUCCESSIVE ITERATIVE METHOD FOR HIGHER-ORDER FRACTIONAL DIFFERENTIAL EQUATIONS INVOLVING STIELTJES INTEGRAL BOUNDARY CONDITIONS

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**Abstract:** In this paper, the existence of positive solutions to fractional differential equations with delayed arguments and Stieltjes integral boundary conditions is discussed. The convergence of successive iterative method of solving such problems is investigated. This allows us to improve some recent works. Some numerical examples illustrate the results.

**Keywords:** fractional differential equations with delayed arguments, Stieltjes integral boundary conditions, successive iterative method, convergence, existence of positive solutions

## 1. Introduction

Put  $J = [0, 1]$ ,  $J_0 = (0, 1)$ ,  $\mathbb{R}_+ = [0, \infty)$ . In this paper, we are interested in the existence of positive solutions to the boundary value problem:

$$\begin{cases} D^q x(t) + f(t, x(\alpha(t)), x(\alpha(t))) = 0, & t \in J_0, n-1 < q \leq n, n \geq 3 \\ x^{(i)}(0) = 0, & i = 0, 1, \dots, n-2 \\ [D^k x(t)]_{t=1} = \lambda[x], & k \text{ is fixed and } k \in [0, n-2] \end{cases} \quad (1)$$

where  $D^q$  is the standard Riemann-Liouville derivative. Here,  $\lambda$  denotes a linear functional given by:

$$\lambda[x] = \int_0^\eta x(t) d\Lambda(t), \quad \eta \in (0, 1] \quad (2)$$

involving the Stieltjes integral with a suitable function  $\Lambda$  of bounded variation. The functional is not assumed to be positive for all positive  $x$ .

Fractional differential equations have been of great interest recently. It is caused both by the intensive development of the theory of fractional calculus itself and by some applications in various fields of sciences and engineering. Recently, many papers have dealt with the existence of positive solutions to the boundary value problems of fractional differential equations. To the author's knowledge, there are several papers in the literature concerning the existence of research of positive solutions for some high order nonlinear fractional differential equations with integral boundary value conditions.

In [1], the authors studied the following higher-order boundary value problem of fractional differential equations

$$\begin{cases} D^q x(t) + f(t, x(t)) = 0, & t \in J_0, \quad n-1 < q \leq n, \quad n \geq 3 \\ x(0) = x'(0) = \dots = x^{n-2}(0) = 0 \\ x^{(k)}(1) = p \int_0^\eta x(s) ds, & p \geq 0, \quad \eta \in (0, 1] \end{cases} \quad (3)$$

where integer  $k$  is fixed and  $k \in \{0, 1, \dots, n-2\}$ . They showed the existence of positive solutions, by using the fixed point index theory. In problem (3),  $k$  is the integer, but in considered problem (1),  $k$  is any fixed number from the interval  $[0, n-2]$ .

In [2, 3], the authors investigated the above problem for  $n = 4$ ,  $k = 0$ , by using Krasnoselskii's fixed point theorem in a cone or the fixed point index theory. In [4], the authors discussed the above problem for  $p = 1$ ,  $n = 4$ ,  $k = 0$ , by constructing two iterative sequences showing their convergence. See also Example 1 connected with the above mentioned papers. Some papers have studied the equation from (3) with the boundary condition  $x(1) = p \int_0^\eta x(s) ds$  replaced by  $x(1) = \lambda[x]$  or a special case of it, see for example, [5–9]. For the case where  $q$  is an integer, see for example [10]. In [11], the author studied problem (1) with  $\lambda[x] = 0$ ,  $k \in [1, n-2]$ , by using Krasnoselskii's fixed point theorem in a cone. Note that, in all the above cited papers, fractional differential equations without deviating arguments  $\alpha$  have been investigated.

Motivated by the above works, in this paper, we establish new existence results for positive solutions to quite general boundary value problems of type (1), by using the method of successive iterations. Some error estimations are given, see Theorem 1 and Example 3. It is worth indicating that the Stieltjes integral boundary condition in problem (1) covers  $m$ -point boundary conditions and integral boundary conditions too. We do not suppose that  $\lambda[x] \geq 0$  for all  $x \geq 0$ , but we allow  $d\Lambda$  to be a signed measure, so we extend the  $m$ -point case to allow some coefficients  $a_i$  of both signs, see Examples 2 and 3.



## 2. Preliminaries

By  $D^q x$ , we denote the Riemann-Liouville fractional derivative of order  $q > 0$ , and by  $I^q x$ , the Riemann-Liouville fractional integral of order  $q > 0$ , see [12–14], so

$$\begin{aligned}
 D^q x(t) &= \frac{1}{\Gamma(n-q)} \left(\frac{d}{dt}\right)^n \int_0^t (t-s)^{-q+n-1} x(s) ds, \quad n = [q] + 1, \quad q > 0, \quad t < 1 \\
 D^n x(t) &= y^{(n)}(t), \quad n \in \{1, 2, 3, \dots\} \\
 I_1^q x(t) &= \frac{1}{\Gamma(q)} \int_0^t (t-s)^{q-1} x(s) ds, \quad q > 0, \quad t < 1
 \end{aligned}
 \tag{4}$$

where  $[q]$  means the integer part of  $q$ .

We require the following assumptions:

$H_1$ :  $f \in C(J \times \mathbb{R}_+ \times \mathbb{R}_+, \mathbb{R}_+)$ ,  $\alpha \in C(J, J)$ ,  $\alpha(t) \leq t$ ,

$H_2$ :  $\Lambda$  is a function of bounded variation on  $[0, \eta]$ ,  $\eta \in (0, 1]$ ,  $n - 1 < q \leq n$ ,  $k$  is fixed,  $k \in [0, n - 2]$ ,  $n \geq 3$  and

$$\begin{aligned}
 \Delta &= \Gamma(q) - \Gamma(q-k) \int_0^\eta t^{q-1} d\Lambda(t) \neq 0, \quad \mathcal{G}(s) = \int_0^\eta G_1(t, s) d\Lambda(t) \\
 G_1(t, s) &= \frac{1}{\Gamma(q)} \begin{cases} t^{q-1}(1-s)^{q-k-1} - (t-s)^{q-1}, & \text{if } s \leq t \\ t^{q-1}(1-s)^{q-k-1}, & \text{if } t \leq s \end{cases}
 \end{aligned}
 \tag{5}$$

Consider the following boundary value problem:

$$\begin{cases} D^q u(t) + y(t) = 0, & t \in J_0, \quad n - 1 < q \leq n, \quad n \geq 3 \\ u^{(i)}(0) = 0, & i = 0, 1, \dots, n - 2 \\ [D^k u(t)]_{t=1} = \lambda[u], & k \text{ is fixed and } k \in [1, n - 2] \end{cases}
 \tag{6}$$

**Lemma 1.** Assume that Assumption  $H_2$  holds. Let  $y \in L(J_0, \mathbb{R})$ . Then, problem (6) has the unique solution given by the following formula

$$u(t) = \int_0^1 G(t, s) y(s) ds
 \tag{7}$$

where

$$G(t, s) = G_1(t, s) + \frac{\Gamma(q-k)}{\Delta} \mathcal{G}(s) t^{q-1}
 \tag{8}$$

*Proof.* The general solution of (6) is given by

$$u(t) = -I^q y(t) + c_1 t^{q-1} + c_2 t^{q-2} + \dots + c_n t^{q-n}
 \tag{9}$$

Indeed,  $c_2 = c_3 = \dots = c_n = 0$  in view of conditions  $u^{(i)}(0) = 0$ ,  $i = 0, 1, \dots, n - 2$ , so

$$u(t) = -I^q y(t) + c_1 t^{q-1}
 \tag{10}$$

Hence, in view of the property  $D^k I^q = I^{q-k}$ ,

$$\begin{aligned}
 D^k u(t) &= -D^k I^q y(t) + c_1 D^k [t^{q-1}] = \\
 &= -\frac{1}{\Gamma(q-k)} \int_0^t (t-s)^{q-k-1} y(s) ds + c_1 \frac{\Gamma(q)}{\Gamma(q-k)} t^{q-k-1}
 \end{aligned}
 \tag{11}$$



This and condition  $[D^k u(t)]_{t=1} = \lambda[u]$  give

$$-\frac{1}{\Gamma(q-k)} \int_0^1 (1-s)^{q-k-1} y(s) ds + c_1 \frac{\Gamma(q)}{\Gamma(q-k)} = \lambda[u] \quad (12)$$

Finding from this  $c_1$  and substituting to (10) we obtain

$$u(t) = \frac{\Gamma(q-k)}{\Gamma(q)} t^{q-1} \lambda[u] + \int_0^1 G_1(t,s) y(s) ds \quad (13)$$

In the next step, we have to eliminate  $\lambda[u]$  from (13). If  $u$  is a solution of (13), then

$$\lambda[u] = \frac{\Gamma(q)}{\Delta} \int_0^1 \mathcal{G}(s) y(s) ds \quad (14)$$

because

$$\begin{aligned} \int_0^\eta \left( \int_0^1 G_1(t,s) y(s) ds \right) d\Lambda(t) &= \\ &= \frac{1}{\Gamma(q)} \int_0^\eta \left( \int_0^1 t^{q-1} (1-s)^{q-k-1} y(s) ds - \int_0^t (t-s)^{q-1} y(s) ds \right) d\Lambda(t) \\ &= \frac{1}{\Gamma(q)} \int_0^1 \left( \int_0^\eta t^{q-1} d\Lambda(t) \right) (1-s)^{q-k-1} y(s) ds \\ &\quad - \frac{1}{\Gamma(q)} \int_0^\eta \left( \int_s^\eta (t-s)^{q-1} d\Lambda(t) \right) y(s) ds = \int_0^1 \mathcal{G}(s) y(s) ds \end{aligned} \quad (15)$$

Substituting it to formula (13) we finally get the assertion of this lemma.  $\blacksquare$

**Remark 1.** Note that  $G$  is the Green function of problem (1).

**Remark 2.** In view of Assumption  $H_2$ , it is easy to see that there exists a positive constant  $d$  such that

$$0 \leq G(t,s) \leq dt^{q-1} \quad (16)$$

### 3. The main results

Define the operator  $T$ , by

$$Tu(t) = \int_0^1 G(t,s) f(s, u(s), u(\alpha(s))) ds \quad (17)$$

In view of Lemma 1, problem (1) is equivalent to the operator equation  $x = Tx$ , and we show that it has a solution.

Let

$$P = \{x \in C(J) : x(t) \geq 0, t \in J\} \quad (18)$$

Indeed,  $P$  is a cone. We define a sub-cone of  $P$ , by

$$D = \{x \in P : \text{there exists a positive constant } K \text{ such that } x(t) \leq Kt^{q-1}\} \quad (19)$$



**Theorem 1.** Let Assumptions  $H_1, H_2$  hold with  $\Delta > 0, \mathcal{G}(s) \geq 0, s \in [0, 1]$ . Moreover, we assume that  $\max_{t \in J} f(t, 0, 0) > 0$ , and

(i) there exist nonnegative constants  $A, B$  such that

$$|f(t, u_1, u_2) - f(t, v_1, v_2)| \leq A|v_1 - u_1| + B|v_2 - u_2| \tag{20}$$

(ii)  $d(A + B) < q$ , where  $d$  is taken from Remark 2.

Then the sequence of functions defined by

$$u_0(t) = 0, \quad u_{n+1}(t) = Tu_n(t), \quad t \in J, \quad n = 0, 1, \dots \tag{21}$$

converges uniformly to the unique solution  $u^* \in D$ . Moreover, we have the error estimation

$$|u^*(t) - u_n(t)| \leq Kt^{q-1}\rho^n, \quad n = 0, 1, \dots \tag{22}$$

where

$$\rho = \frac{d(A+B)}{q}, \quad K = \frac{Md}{1-\rho}, \quad M = \max_{t \in J} f(t, 0, 0) \tag{23}$$

*Proof.* Indeed,  $u_n \in C(J, \mathbb{R}_+)$ . Put

$$w_n(t) = |u_n(t) - u_{n-1}(t)|, \quad n = 1, 2, \dots \tag{24}$$

Then,

$$\begin{aligned} w_{n+1}(t) &= |Tu_n(t) - Tu_{n-1}(t)| \\ &\leq \int_0^1 G(t, s) |f(s, u_n(s), u_n(\alpha(s))) - f(s, u_{n-1}(s), u_{n-1}(\alpha(s)))| ds \end{aligned} \tag{25}$$

so using condition (i),

$$w_{n+1}(t) \leq dt^{q-1} \int_0^1 [Aw_n(s) + Bw_n(\alpha(s))] ds, \quad t \in J, \quad n = 1, 2, \dots \tag{26}$$

Indeed,

$$\begin{aligned} w_1(t) &= |Tu_0(t)| = \int_0^1 G(t, s) f(s, 0, 0) ds \leq Mdt^{q-1} \\ w_2(t) &\leq dt^{q-1} \int_0^1 [Aw_1(s) + Bw_1(\alpha(s))] ds \leq Mdt^{q-1}\rho \end{aligned} \tag{27}$$

because  $0 \leq G(t, s) \leq dt^{q-1}, \alpha(s) \leq s$ .

Now, we have to prove that

$$w_n(t) \leq Mdt^{q-1}\rho^{n-1} \equiv z_n(t), \quad n = 1, 2, \dots \tag{28}$$

Assume that (28) holds for some integer  $n = m > 1$ . Using (26) and  $w_m(\alpha(s)) \leq z_m(s)$ , we obtain

$$\begin{aligned} w_{m+1}(t) &\leq dt^{q-1} \int_0^1 [Aw_m(s) + Bw_m(\alpha(s))] ds \\ &\leq d(A+B)t^{q-1} \int_0^1 z_m(s) ds = z_{m+1}(t) \end{aligned} \tag{29}$$

This and the mathematical induction show that (28) holds.



Now, we have to show that the sequence  $\{u_n\}$  is convergent. First, we note that

$$u_n(t) = u_0(t) + \sum_{j=1}^n [u_j(t) - u_{j-1}(t)], \quad n = 1, 2, \dots \quad (30)$$

In view of (28), we see that

$$\sum_{j=1}^{\infty} w_j(t) \leq M dt^{q-1} \sum_{j=1}^{\infty} \rho^{j-1} = M dt^{q-1} \frac{1}{1-\rho} < \frac{Md}{1-\rho} = K \quad (31)$$

Using the Weierstrass test, this shows that the series

$$u_0(t) + \sum_{j=1}^{\infty} [u_j(t) - u_{j-1}(t)] \quad (32)$$

is uniformly convergent. This asserts that the sequence  $\{u_n\}$  is uniformly convergent too. Indeed,  $u^*(t) = \lim_{n \rightarrow \infty} u_n(t)$  and  $u^* \in C(J, \mathbb{R}_+)$ . Obviously, taking the limit  $n \rightarrow \infty$ , we see that  $u^*(t) = Tu^*(t)$ ,  $t \in J$ , so  $u^* \in C(J, \mathbb{R}_+)$  is a solution of problem (1).

Moreover,

$$0 \leq u_n(t) \leq \sum_{j=1}^n w_j(t) \leq \sum_{j=1}^{\infty} w_j(t) \leq K t^{q-1}, \quad n = 1, 2, \dots \quad (33)$$

This proves that  $u_n, u^* \in D$ ,  $n = 0, 1, \dots$ .

Now, we have to prove that  $u^*$  is a unique solution of (1) in  $D$ . Suppose that  $v$  is another solution distinct from  $u^*$  and  $v \in D$ . Put  $V(t) = |u^*(t) - v(t)|$ . Then

$$\begin{aligned} V(t) &= |Tv(t) - Tu^*(t)| \\ &\leq \int_0^1 G(t,s) |f(s, v(s), v(\alpha(s))) - f(s, u^*(s), u^*(\alpha(s)))| ds \\ &\leq dt^{q-1} \int_0^1 [AV(s) + BV(\alpha(s))] ds \end{aligned} \quad (34)$$

so

$$V(t) \leq 2dt^{q-1}K(A+B) \int_0^1 s^{q-1} ds = 2Kt^{q-1}\rho \quad (35)$$

because

$$V(t) \leq 2Kt^{q-1} \quad (36)$$

This and the previous relation on  $V$  give

$$V(t) \leq 2Kt^{q-1}\rho^2 \quad (37)$$

Repeating it, we can show, by induction, that

$$V(t) \leq 2Kt^{q-1}\rho^n, \quad n = 1, 2, \dots \quad (38)$$

so  $\rho^n \rightarrow 0$ . This immediately shows that  $u^*$  is the unique solution of (1) in  $D$ .



Now, we need to obtain the error estimation. Put  $Z_n(t) = |u^*(t) - u_n(t)|$ . Then

$$\begin{aligned} Z_{n+1}(t) &= |Tu^*(t) - T_n(t)| \\ &\leq \int_0^1 G(t,s) |f(s, u^*(s), u^*(\alpha(s))) - f(s, u_n(s), u_n(\alpha(s)))| ds \\ &\leq dt^{q-1} \int_0^1 [AZ_n(s) + BZ_n(\alpha(s))] ds, \quad n = 0, 1, \dots \end{aligned} \tag{39}$$

Hence

$$Z_1(t) \leq dt^{q-1} \int_0^1 [Au^*(s) + Bu^*(\alpha(s))] ds \leq Kt^{q-1}\rho \tag{40}$$

because  $u^*(t) \leq Kt^{q-1}$ .

By induction in  $n$ , we can show that  $Z_n(t) \leq Kt^{q-1}\rho^n$ , so

$$|u^*(t) - u_n(t)| \leq Kt^{q-1}\rho^n, \quad n = 0, 1, \dots \tag{41}$$

This ends the proof. ■

### 4. Examples

**Example 1.** Let  $d\Lambda(t) = c dt$ ,  $c \geq 0$ . Indeed,  $\mathcal{G}(s) \geq 0$ ,  $s \in [0, 1]$ . Moreover,  $\Delta > 0$  provided that

$$0 \leq c \frac{\eta^q}{q} < \frac{\Gamma(q)}{\Gamma(q-k)} \tag{42}$$

If  $k \in \{0, 1, \dots, n-2\}$ , then (42) takes the form

$$0 \leq c \frac{\eta^q}{q} < 1 \text{ if } k = 0 \tag{43}$$

$$0 \leq c \frac{\eta^q}{q} < \prod_{i=1}^k (q-i) \text{ if } k \in \{1, 2, \dots, n-2\} \tag{44}$$

Condition (43) appeared in papers [2, 3] for  $n = 4$ ; in [4] for  $c = 1$ ,  $n = 4$ . The case with  $c \geq 0$  has also been discussed in paper [1] for  $k \in \{0, 1, \dots, n-2\}$  with conditions (43) and (44).

**Example 2.** Let

$$\lambda[x] = \sum_{i=1}^m a_i x(\eta_i), \quad a_i \in \mathbb{R}, \quad i = 1, 2, \dots, m, \quad 0 < \eta_1 < \eta_2 < \dots < \eta_m \leq \eta < 1 \tag{45}$$

Then

$$\mathcal{G}(s) = \sum_{i=1}^m a_i G_1(\eta_i, s) \tag{46}$$



so

$$\mathcal{G}(s) = \frac{1}{\Gamma(q)} \begin{cases} \sum_{i=1}^m a_i W_1(\eta_i, s), & 0 \leq s \leq \eta_1 \\ a_1 W_2(\eta_1, s) + \sum_{i=2}^m a_i W_1(\eta_i, s), & \eta_1 < s \leq \eta_2 \\ \dots, \dots \\ \sum_{i=1}^{m-1} a_i W_2(\eta_i, s) + a_m W_1(\eta_m, s), & \eta_{m-1} < s \leq \eta_m \\ \sum_{i=1}^m a_i W_2(\eta_i, s), & \eta_m < s \leq 1 \end{cases} \tag{47}$$

where

$$W_1(t, s) = \frac{1}{\Gamma(q)} [t^{q-1}(1-s)^{q-k-1} - (t-s)^{q-1}] \text{ if } s \leq t$$

$$W_2(t, s) = \frac{1}{\Gamma(q)} t^{q-1}(1-s)^{q-k-1} \text{ if } t \leq s$$
(48)

We need  $\mathcal{G}(s) \geq 0, s \in [0, 1]$  which is automatic if  $a_i \geq 0, i = 1, 2, \dots, m$ , because  $H_1$  and  $H_2$  are nondecreasing. Now, we also need  $\Delta > 0$ , which holds if

$$0 \leq \sum_{i=1}^m a_i \eta_i^{q-1} < \frac{\Gamma(q)}{\Gamma(q-k)} \tag{49}$$

**Example 3.** Now, we consider the sign changing case. Let  $\lambda[x] = 2^{q-1}x(\frac{\eta}{2}) - x(\eta), \eta \in (0, 1)$ . Then  $\mathcal{G}(s) = 2^{q-1}G_1(\frac{\eta}{2}, s) - G_1(\eta, s)$ , so

$$\mathcal{G}(s) = \begin{cases} 2^{q-1}W_1(\frac{\eta}{2}, s) - W_1(\eta, s), & 0 \leq s < \frac{\eta}{2} \\ 2^{q-1}W_2(\frac{\eta}{2}, s) - W_1(\eta, s), & \frac{\eta}{2} \leq s < \eta \\ 2^{q-1}W_2(\frac{\eta}{2}, s) - W_2(\eta, s), & \eta \leq s \leq 1 \end{cases} \tag{50}$$

where  $W_1$  and  $W_2$  are defined as in Example 2. It is easy to verify that  $\mathcal{G}(s) \geq 0, s \in [0, 1]$ . Moreover,

$$\int_0^\eta t^{q-1} d\Lambda(t) = 2^{q-1} \left(\frac{\eta}{2}\right)^{q-1} - \eta^{q-1} = 0 \tag{51}$$

so  $\Delta = \Gamma(q) > 0$ .

### 5. Numerical example

Consider the following problem

$$\begin{cases} D^q x(t) = g(t) + a \sin x(t) + bx(\sqrt{t}) \equiv f(t, x(t), x(\alpha(t))), & t \in (0, 1) \\ x(0) = x'(0) = 0, [D^k x(t)]_{t=1} = c \int_0^\eta x(s) ds \end{cases} \tag{52}$$

with  $g \in C([0, 1], \mathbb{R}_+), g(0) = 1, q = \frac{7}{2}, a, b, c \in \mathbb{R}_+, a + b = 5, k = \frac{1}{2}, \eta = \frac{3}{4}$ . Hence

$$\Delta = \Gamma(q) - c\Gamma(q-k) \int_0^\eta t^{q-1} dt = \frac{15}{8} \sqrt{\pi} - c \frac{27\sqrt{3}}{224} \tag{53}$$



If we assume that

$$c < \frac{140\sqrt{\pi}}{9\sqrt{3}} \approx 15.918 \tag{54}$$

then  $\Delta > 0$ . Moreover,  $M = 1$ ,  $A + B = 5$ , and

$$\begin{aligned} \mathcal{G}(s) &\leq \frac{9\sqrt{3}}{280\sqrt{\pi}} c, & G_1(t, s) &\leq \frac{8}{15\sqrt{\pi}} t^{\frac{5}{2}} \\ G(t, s) &\leq \left( \frac{8}{15\sqrt{\pi}} + \frac{168\sqrt{3}c}{35(140\pi - 9\sqrt{3}\pi c)} \right) t^{\frac{5}{2}} = dt^{\frac{5}{2}}, & d &= d(c) \end{aligned} \tag{55}$$

Assume that condition (54) holds. Then, in view of Theorem 1, problem (52) has a unique positive solution  $u^* \in D$ . This solution is the limit of the sequence of functions defined by

$$u_0(t) = 0, \quad u_{n+1}(t) = Tu_n(t), \quad t \in J, \quad n = 0, 1, \dots \tag{56}$$

and we have the error estimation

$$|u^*(t) - u_n(t)| \leq Kt^{\frac{5}{2}}\rho^n, \quad n = 0, 1, \dots \tag{57}$$

with

$$\rho = \frac{10d}{7}, \quad K = \frac{d}{1-\rho} \tag{58}$$

The estimation (57) depends on  $c$ , because  $d = d(c)$ . Now, we are going to discuss the estimation (57) for  $c = 1$ ,  $c = 5$  and  $c = 10$ .

1. Put  $c = 1$ . Then,  $d \approx 0.321$ ,  $\rho \approx 0.459$ ,  $K \approx 0.593$ . Moreover,

$$0 \leq u^*(t) \leq 0.593t^{\frac{5}{2}}, \quad |u^*(t) - u_5(t)| \leq 0.002t^{\frac{5}{2}} \tag{59}$$

2. Put  $c = 5$ . Then,  $d \approx 0.439$ ,  $\rho \approx 0.627$ ,  $K \approx 1.176$ . Moreover,

$$0 \leq u^*(t) \leq 1.176t^{\frac{5}{2}}, \quad |u^*(t) - u_5(t)| \leq 0.114t^{\frac{5}{2}}, \quad |u^*(t) - u_{10}(t)| \leq 0.003t^{\frac{5}{2}} \tag{60}$$

3. Put  $c = 10$ . Then,  $d \approx 0.594$ ,  $\rho \approx 0.848$ ,  $K \approx 3.912$ . Moreover,

$$\begin{aligned} 0 \leq u^*(t) &\leq 3.912t^{\frac{5}{2}}, & |u^*(t) - u_5(t)| &\leq 1.715t^{\frac{5}{2}}, & |u^*(t) - u_{10}(t)| &\leq 0.752t^{\frac{5}{2}} \\ |u^*(t) - u_{20}(t)| &\leq 0.145t^{\frac{5}{2}}, & |u^*(t) - u_{50}(t)| &\leq 0.001t^{\frac{5}{2}} \end{aligned} \tag{61}$$

Conclusion. The results presented above demonstrate that we have quite good estimation for  $c = 1$  finding only the iterations  $u_n$  from 1 to 5, however, the iterations  $u_n$  from 1 do 50 are needed to get a similar order of estimation for  $c = 10$ .

### References

- [1] Wang L and Zhang X 2014 *J. Appl. Math. Comput.* **44** 293
- [2] Zhang X 2012 *Bound. Value Probl.* **212** 212
- [3] Zhang X, Wang L and Sun Q 2014 *Appl. Math. Comput.* **226** 708
- [4] Jiang M and Zhong S 2014 *Appl. Math. Lett.* **38** 94
- [5] Wang Y, Liu L and Wu Y 2011 *Nonlinear Anal.* **74** 3599
- [6] Wang Y and Yang Y 2014 *J. Appl. Math. Comput.* **45** 99
- [7] Zhang X and Han Y 2012 *Appl. Math. Lett.* **25** 555



- [8] Feng M, Zhang X and Gao W 2011 *Bound. Value Probl.*, Art. ID 720702 20
- [9] Sun Y and Zhao M 2014 *Appl. Math. Lett.* **34** 17
- [10] Webb J R L 2009 *Nonlinear Anal.* **71** 1933
- [11] Goodrich Ch 2010 *Appl. Math. Lett.* **23** 1050
- [12] Kilbas A A, Srivastava H R and Trujillo J J 2006 *Theory and Applications of Fractional Differential Equations*, North-Holland Mathematics Studies, Elsevier, **204**
- [13] Lakshmikantham V, Leela S and Vasundhara J 2009 *Theory of Fractional Dynamic Systems*, Cambridge Academic Publishers
- [14] Samko S G, Kilbas A A and Marichev O I 1993 *Fractional Integrals and Derivatives: Theory and Applications*, Gordon and Breach Science Publishers