



Nonlinear boundary value problems for second order differential equations with causal operators

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Abstract

In this paper we deal with second order differential equations with causal operators. To obtain sufficient conditions for existence of solutions we use a monotone iterative method. We investigate both differential equations and differential inequalities. An example illustrates the results obtained.

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1. Introduction

Let $J = [0, T]$, $E = C(J, \mathbb{R})$ and $Q \in C(E, E)$. We shall say that Q is a causal operator, or nonanticipative, if the following property holds: for each couple of elements of E such that $u(s) = v(s)$ for $0 \leq s \leq t$, there results $(Qu)(s) = (Qv)(s)$ for $0 \leq s \leq t$ with $t < T$ arbitrary, for details see [1].

Note that $(Q_1x)(t) = \int_0^t W(t, s, x(s)) ds$, $t \in [0, c]$ and $(Q_2x)(t) = h(t, x(t))$, $t \in [0, c]$ are examples of causal operators. Indeed, W and h are continuous functions with values in \mathbb{R}^p . In the literature operator Q_1 is known under the name “Volterra operator” and Q_2 is known as “Niemytskii operator.”

In this paper, we investigate nonlinear four-point boundary value problems for second order differential equations with a causal operator Q of the form

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$$\begin{cases} x''(t) = (Qx)(t), & t \in J = [0, T], \\ 0 = g_1(x(0), x(\delta)), & 0 < \delta < T, \\ 0 = g_2(x(T), x(\gamma)), & 0 < \gamma < T, \end{cases} \quad (1)$$

where $g_1, g_2 \in C(\mathbb{R} \times \mathbb{R}, \mathbb{R})$. Functional equations with causal operators are discussed in book [1], see also the references therein. To obtain approximate solutions of nonlinear differential problems we can apply the monotone iterative technique. This technique is well known and we have a lot of applications of this method to differential equations both initial and boundary conditions, see for example [3–6,8–12]. Recently, this method is also applied to first order differential equations with causal operators, see [2] (periodic conditions) and also [7] (nonlinear boundary conditions). This paper extends the application of this method to nonlinear four-point boundary problems for second order differential equations with causal operators. In Section 2, we discuss differential inequalities with positive linear operators to obtain a comparison result. This result is useful to prove the existence of solutions of problems of type (1). In Section 3, we formulate sufficient conditions which guarantee that problem (1) has extremal solutions. A one-sided Lipschitz condition (with corresponding linear operators) is imposed on the causal operator Q . The problem when (1) has the unique solution is also investigated. At the end of this section, an example is added to illustrate theoretical results. In Section 4, we discuss the situation when problem (1) has quasi-solutions and then also the unique solution.

2. Differential inequalities

To apply the monotone iterative method to problems of type (1) we need a fundamental result on differential inequalities.

Lemma 1. *Assume that:*

$$H_1: M \in C(J, [0, \infty)), M(t) > 0, t \in (0, T), M(0) \geq 0, M(T) \geq 0,$$

$$H_2: \mathcal{L} \in C(E, E) \text{ is a positive linear causal operator i.e. } (\mathcal{L}m)(t) \geq 0, t \in J \text{ provided that } m(t) \geq 0 \text{ on } J,$$

$$H_3: \rho \equiv \int_0^T (\int_s^T [M(t) + (\mathcal{L}\mathbf{1})(t)] dt) ds \leq 1, \text{ where } \mathbf{1}(t) = 1, t \in J.$$

Let $p \in C^2(J, \mathbb{R})$ and

$$\begin{cases} p''(t) \geq M(t)p(t) + (\mathcal{L}p)(t), & t \in J, \\ p(0) \leq 0, & p(T) \leq 0. \end{cases}$$

Then $p(t) \leq 0$ on J .

Proof. Suppose that the inequality $p(t) \leq 0, t \in J$ is not true. It means that there exists t_0 such that

$$p(t_0) = \max_{t \in J} p(t) = d > 0.$$

Note that $p''(t_0) \leq 0$ and $p'(t_0) = 0, t_0 \in (0, T)$.

Case 1. Assume that $p(t) \geq 0, t \in [0, t_0]$. Then

$$0 \geq p''(t_0) \geq M(t_0)d > 0.$$

It is a contradiction.



Case 2. There exists $t_1 \in [0, t_0]$ such that $p(t_1) < 0$. Then there exists $\xi \in [0, t_0]$ such that

$$p(\xi) = \min_{t \in [0, t_0]} p(t) < 0.$$

It yields

$$p''(t) \geq p(\xi)[M(t) + (\mathcal{L}\mathbf{1})(t)], \quad t \in [0, t_0].$$

Integrating the above inequality from s to t_0 we get

$$-p'(s) = p'(t_0) - p'(s) \geq p(\xi) \int_s^{t_0} [M(t) + (\mathcal{L}\mathbf{1})(t)] dt.$$

Next, we integrate the above inequality from ξ to t_0 to obtain

$$p(\xi) > -p(t_0) + p(\xi) \geq p(\xi) \int_{\xi}^{t_0} \left(\int_s^{t_0} [M(t) + (\mathcal{L}\mathbf{1})(t)] dt \right) ds.$$

Dividing by $p(\xi)$, we finally get

$$1 < \int_0^T \left(\int_s^T [M(t) + (\mathcal{L}\mathbf{1})(t)] dt \right) ds = \rho \leq 1$$

since $p(\xi) < 0$. It is a contradiction. This proves the lemma. \square

Remark 1. Let the operator \mathcal{L} be defined by

$$(\mathcal{L}p)(t) = \sum_{i=1}^r L_i(t)p(\alpha_i(t)),$$

where $L_i \in C(J, \mathbb{R}_+)$, $\alpha_i \in C(J, J)$, $\alpha_i(t) \leq t$, $i = 1, 2, \dots, r$. Then

$$\rho = \int_0^T \left(\int_s^T \left[M(t) + \sum_{i=1}^r L_i(t) \right] dt \right) ds.$$

If $M(t) = L_0 > 0$, $L_i(t) = L_i > 0$, $t \in J$, $i = 1, 2, \dots, r$. Then

$$\rho = \frac{1}{2} T^2 \sum_{i=0}^r L_i.$$

3. Extremal solutions. Unique solution

A function $y_0 \in C^2(J, \mathbb{R})$ is said to be a lower solution of (1) if

$$y_0''(t) \geq (Qy_0)(t), \quad t \in J, \quad g_1(y_0(0), y_0(\delta)) \leq 0, \quad g_2(y_0(T), y_0(\gamma)) \leq 0.$$

A function $z_0 \in C^2(J, \mathbb{R})$ is said to be an upper solution of problem (1) if the above inequalities are reversed.

To show that problem (1) has a solution we construct two sequences which elements are solutions of corresponding linear problems. Existence of solutions of such problems is discussed in the next theorem.



Theorem 1. Let assumptions H_1 – H_3 be satisfied. In addition we assume that

H_4 : $Q \in C(E, E)$ is a causal operator, $g_i \in C(\mathbb{R} \times \mathbb{R}, \mathbb{R})$, $i = 1, 2$,

H_5 : $y_0, z_0 \in C^2(J, \mathbb{R})$ are lower and upper solutions of problem (1), respectively, and $y_0(t) \leq z_0(t)$, $t \in J$,

H_6 : $m \in C^2(J, \mathbb{R})$ and $y_0(t) \leq m(t) \leq z_0(t)$, $t \in J$,

H_7 : the following condition

$$(Qu)(t) - (Q\bar{u})(t) \geq -M(t)[\bar{u}(t) - u(t)] - (\mathcal{L}(\bar{u} - u))(t) \quad (2)$$

holds for $y_0(t) \leq u(t) \leq \bar{u}(t) \leq z_0(t)$,

H_8 : g_i , $i = 1, 2$ are nonincreasing with respect to the second variable and there exist positive constants a, b such that

$$g_1(\bar{u}, v) - g_1(u, v) \leq a(\bar{u} - u),$$

$$g_2(\bar{u}_1, v_1) - g_2(u_1, v_1) \leq b(\bar{u}_1 - u_1)$$

for $y_0(0) \leq u \leq \bar{u} \leq z_0(0)$, $y_0(T) \leq u_1 \leq \bar{u}_1 \leq z_0(T)$, $y_0(\delta) \leq v \leq z_0(\delta)$, $y_0(\gamma) \leq v_1 \leq z_0(\gamma)$.

Let $y \in C^2(J, \mathbb{R})$ and

$$\begin{cases} y''(t) = M(t)y(t) + (\mathcal{L}y)(t) + \sigma(t), & t \in J, \\ y(0) = k_1 \in \mathbb{R}, & y(T) = k_2 \in \mathbb{R}, \end{cases} \quad (3)$$

where

$$\sigma(t) = (Qm)(t) - M(t)m(t) - (\mathcal{L}m)(t),$$

$$k_1 = -\frac{1}{a}g_1(m(0), m(\delta)) + m(0), \quad k_2 = -\frac{1}{b}g_2(m(T), m(\gamma)) + m(T).$$

Then problem (3) has a unique solution $y \in C^2(J, \mathbb{R})$ and $y \in [y_0, z_0]_*$, where $[y_0, z_0]_* = \{w \in C^2(J, \mathbb{R}) : y_0(t) \leq w(t) \leq z_0(t), t \in J\}$.

Proof. Note that problem (3) has at most one solution. To see it let us assume that it has two distinct solutions $z, w \in C^2(J, \mathbb{R})$. Put $p = z - w$. Then $p(0) = p(T) = 0$ and $p''(t) = M(t)p(t) + (\mathcal{L}p)(t)$ on J . In view of assumption H_3 and Lemma 1, we have $p \leq 0$, so $z(t) \leq w(t)$, $t \in J$. Now putting $p = w - z$, we have $w(t) \leq z(t)$, $t \in J$, by Lemma 1. Hence $w(t) = z(t)$, $t \in J$.

It shows that problem (3) has at most one solution. Denote this solution by y . We need to show that $y \in [y_0, z_0]_*$. Put $p = y_0 - y$. Then, in view of assumptions H_5, H_6, H_8 , we have

$$\begin{aligned} p(0) &= y_0(0) + \frac{1}{a}[g_1(m(0), m(\delta)) - g_1(y_0(0), y_0(\delta)) + g_1(y_0(0), y_0(\delta))] - m(0) \\ &\leq y_0(0) + \frac{1}{a}[g_1(m(0), y_0(\delta)) - g_1(y_0(0), y_0(\delta))] - m(0) \leq 0, \end{aligned}$$

$$\begin{aligned} p(T) &= y_0(T) + \frac{1}{b}[g_2(m(T), m(\gamma)) - g_2(y_0(T), y_0(\gamma)) + g_2(y_0(T), y_0(\gamma))] - m(T) \\ &\leq y_0(T) + \frac{1}{b}[g_2(m(T), y_0(\gamma)) - g_2(y_0(T), y_0(\gamma))] - m(T) \leq 0. \end{aligned}$$

Moreover,

$$\begin{aligned}
 p''(t) &\geq (Qy_0)(t) - (Qm)(t) - M(t)[y(t) - m(t)] - (\mathcal{L}(y - m))(t) \\
 &\geq -M(t)[m(t) - y_0(t)] - (\mathcal{L}(m - y_0))(t) - M(t)[y(t) - m(t)] - (\mathcal{L}(y - m))(t) \\
 &= M(t)p(t) + (\mathcal{L}p)(t),
 \end{aligned}$$

by assumption H_7 . This result and Lemma 1 show that $y_0(t) \leq m(t)$, $t \in J$. Similarly, we can show that $m(t) \leq z_0(t)$, $t \in J$. It means that if problem (3) has a solution then it belongs to $[y_0, z_0]_*$.

Now we need to show that problem (3) has a solution. To do it we write problem (3) in the following way

$$y(t) = \int_0^T G(t, s) [M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)] ds + \frac{k_2 - k_1}{T}t + k_1, \quad t \in J, \quad (4)$$

where the Green function G is defined by

$$G(t, s) = -\frac{1}{T} \begin{cases} (T-t)s & \text{if } 0 \leq s \leq t \leq T, \\ (T-s)t & \text{if } 0 \leq t \leq s \leq T. \end{cases}$$

Denote by A the operator defined by the right-hand side of (4). Note that E is a Banach space with the norm $\|y\| = \max_{t \in J} \|y(t)\|$. We employ Schauder's fixed point theorem to show that operator A has a fixed point. Let $y \in E$. Note that $M(t)y(t) + (\mathcal{L}y)(t) + \sigma(t)$ is bounded in J , so operator $A: E \rightarrow E$ is continuous and bounded. In fact A is a compact map. Let

$$|M(t)y(t) + (\mathcal{L}y)(t) + \sigma(t)| \leq K, \quad K > 0.$$

Take $t_1, t_2 \in J$, $t_1 < t_2$ such that $|t_1 - t_2| < \frac{T\epsilon}{4KT^2 + |k_2 - k_1|}$ for $\epsilon > 0$. Then we have

$$\begin{aligned}
 &|Ay(t_1) - Ay(t_2)| \\
 &= \left| \int_0^T [G(t_1, s) - G(t_2, s)] \{M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)\} ds \right| + k|t_1 - t_2| \\
 &= \frac{1}{T} \left| (t_1 - t_2) \int_0^{t_1} s \{M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)\} ds \right. \\
 &\quad \left. - t_1 \int_{t_1}^{t_2} (T-s) \{M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)\} ds \right. \\
 &\quad \left. + (T-t_2) \int_{t_1}^{t_1} s \{M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)\} ds \right. \\
 &\quad \left. + (t_2 - t_1) \int_{t_2}^T (T-s) \{M(s)y(s) + (\mathcal{L}y)(s) + \sigma(s)\} ds \right| + k|t_1 - t_2| \\
 &\leq (4KT + k)|t_1 - t_2| < \epsilon,
 \end{aligned}$$

where $k = \frac{|k_2 - k_1|}{T}$. Consequently $A: E \rightarrow E$ is compact. Schauder's fixed point theorem guarantees that A has a fixed point in E . In view of (4), we have $y(0) = k_1$, $y(T) = k_2$, and y'' exists



and $y'' \in E$. Moreover, $y \in C^2(J, \mathbb{R})$ and $y''(t) = M(t)y(t) + (\mathcal{L}y)(t) + \sigma(t)$, so y is a solution of problem (3). It shows that y is the unique solution of (3). This ends the proof. \square

Theorem 2. *Let assumptions from H_1 – H_5 and H_7 , H_8 be satisfied. Then problem (1) has extremal solutions in the sector $[y_0, z_0]_*$.*

Proof. Let us define two sequences $\{y_n, z_n\}$ by relations:

$$\begin{cases} y_n''(t) = (Qy_{n-1})(t) + M(t)[y_n(t) - y_{n-1}(t)] + (\mathcal{L}(y_n - y_{n-1}))(t), & t \in J, \\ y_n(0) = -\frac{1}{a}g_1(y_{n-1}(0), y_{n-1}(\delta)) + y_{n-1}(0), \\ y_n(T) = -\frac{1}{b}g_2(y_{n-1}(T), y_{n-1}(\gamma)) + y_{n-1}(T), \end{cases}$$

$$\begin{cases} z_n''(t) = (Qz_{n-1})(t) + M(t)[z_n(t) - z_{n-1}(t)] + (\mathcal{L}(z_n - z_{n-1}))(t), & t \in J, \\ z_n(0) = -\frac{1}{a}g_1(z_{n-1}(0), z_{n-1}(\delta)) + z_{n-1}(0), \\ z_n(T) = -\frac{1}{b}g_2(z_{n-1}(T), z_{n-1}(\gamma)) + z_{n-1}(T) \end{cases}$$

for $n = 1, 2, \dots$. Note that y_1, z_1 are well defined, by Theorem 1.

First of all we want to show that

$$y_0(t) \leq y_1(t) \leq z_1(t) \leq z_0(t), \quad t \in J. \quad (5)$$

Put $p = y_0 - y_1$. Then

$$\begin{aligned} p(0) &= y_0(0) + \frac{1}{a}g_1(y_0(0), y_0(\delta)) - y_0(0) \leq 0, \\ p(T) &= y_0(T) + \frac{1}{b}g_2(y_0(T), y_0(\gamma)) - y_0(T) \leq 0, \end{aligned}$$

by assumption H_5 . Moreover,

$$\begin{aligned} p''(t) &\geq (Qy_0)(t) - (Qy_0)(t) - M(t)[y_1(t) - y_0(t)] - (\mathcal{L}(y_1 - y_0))(t) \\ &= M(t)p(t) + (\mathcal{L}p)(t), \end{aligned}$$

by assumption H_5 . This result and Lemma 1 show that $y_0(t) \leq y_1(t)$, $t \in J$. Similarly, we can show that $z_1(t) \leq z_0(t)$, $t \in J$. Now let $p = y_1 - z_1$. Then

$$\begin{aligned} p(0) &= \frac{1}{a}[g_1(z_0(0), z_0(\delta)) - g_1(y_0(0), y_0(\delta))] + y_0(0) - z_0(0) \\ &\leq \frac{1}{a}[g_1(z_0(0), y_0(\delta)) - g_1(y_0(0), y_0(\delta))] + y_0(0) - z_0(0) \\ &\leq z_0(0) - y_0(0) + y_0(0) - z_0(0) = 0, \\ p(T) &= y_0(T) + \frac{1}{b}[g_2(z_0(T), z_0(\gamma)) - g_2(y_0(T), y_0(\gamma))] - z_0(T) \leq 0, \end{aligned}$$

by assumption H_8 . Moreover,

$$\begin{aligned}
 p''(t) &= (Qy_0)(t) - (Qz_0)(t) + M(t)[y_1(t) - y_0(t) - z_1(t) + z_0(t)] \\
 &\quad + (\mathcal{L}(y_1 - y_0 - z_1 + z_0))(t) \\
 &\geq -M(t)[z_0(t) - y_0(t)] - (\mathcal{L}(z_0 - y_0))(t) \\
 &\quad + M(t)[y_1(t) - y_0(t) - z_1(t) + z_0(t)] + (\mathcal{L}(y_1 - y_0 - z_1 + z_0))(t) \\
 &= M(t)p(t) + (\mathcal{L}p)(t),
 \end{aligned}$$

by assumption H₇. In view of Lemma 1, $y_1(t) \leq z_1(t)$, $t \in J$. It proves (5).

Now we show that y_1 is a lower solution of problem (1). Note that

$$\begin{aligned}
 0 &= y_1(0) + \frac{1}{a}[g_1(y_0(0), y_0(\delta)) - g_1(y_1(0), y_1(\delta)) + g_1(y_1(0), y_1(\delta))] - y_0(0) \\
 &\geq y_1(0) + \frac{1}{a}[g_1(y_0(0), y_1(\delta)) - g_1(y_1(0), y_1(\delta)) + g_1(y_1(0), y_1(\delta))] - y_0(0) \\
 &\geq y_1(0) - y_0(0) - y_1(0) + y_0(0) + \frac{1}{a}g_1(y_1(0), y_1(\delta)) = \frac{1}{a}g_1(y_1(0), y_1(\delta)), \\
 0 &= y_1(T) + \frac{1}{b}[g_2(y_0(T), y_0(\gamma)) - g_2(y_1(T), y_1(\gamma)) + g_2(y_1(T), y_1(\gamma))] - y_0(T) \\
 &\geq \frac{1}{b}g_2(y_1(T), y_1(\gamma)),
 \end{aligned}$$

by assumption H₈. Moreover,

$$\begin{aligned}
 y_1''(t) &= (Qy_0)(t) - (Qy_1)(t) + (Qy_1)(t) + M(t)[y_1(t) - y_0(t)] + (\mathcal{L}(y_1 - y_0))(t) \\
 &\geq -M(t)[y_1(t) - y_0(t)] - (\mathcal{L}(y_1 - y_0))(t) + (Qy_1)(t) + M(t)[y_1(t) - y_0(t)] \\
 &\quad + (\mathcal{L}(y_1 - y_0))(t) = (Qy_1)(t),
 \end{aligned}$$

by assumption H₇. It proves that y_1 is a lower solution of (1). Similarly, we can prove that z_1 is an upper solution of problem (1).

By mathematical induction we can show that

$$y_0(t) \leq \dots \leq y_{n-1}(t) \leq y_n(t) \leq z_n(t) \leq z_{n-1}(t) \leq \dots \leq z_0(t), \quad t \in J$$

for $n = 1, 2, \dots$

It implies that $\{y_n\}$, $\{z_n\}$ are uniformly bounded. We can show that they are equicontinuous on J . The Arzeli–Ascoli theorem guarantees the existence of subsequences $\{y_{n_k}\}$, $\{z_{n_k}\}$ and functions $\bar{y}, \bar{z} \in C(J, \mathbb{R})$ with y_{n_k}, z_{n_k} converging uniformly on J to \bar{y} and \bar{z} , respectively, if $n_k \rightarrow \infty$. However, since the sequences $\{y_n\}$, $\{z_n\}$ are monotonic, we conclude that the whole sequences $\{y_n\}$, $\{z_n\}$ converge uniformly on J to \bar{y} and \bar{z} , respectively, if $n \rightarrow \infty$. Indeed, \bar{y}, \bar{z} are solutions of problem (1).

We need to show now that (\bar{y}, \bar{z}) are extremal solutions of problem (1) in the segment $[y_0, z_0]_*$. To prove it, we assume that \tilde{y} is another solution of problem (1), and $y_{n-1}(t) \leq \tilde{y}(t) \leq z_{n-1}(t)$, $t \in J$ for some positive integer n . Put $p(t) = y_n(t) - \tilde{y}(t)$, $q(t) = \tilde{y}(t) - z_n(t)$, $t \in J$. Hence

$$\begin{aligned}
 p(0) &= y_{n-1}(0) - \tilde{y}(0) + \frac{1}{a}[g_1(\tilde{y}(0), \tilde{y}(\delta)) - g_1(y_{n-1}(0), y_{n-1}(\delta))] \\
 &\leq y_{n-1}(0) - \tilde{y}(0) + \frac{1}{a}[g_1(\tilde{y}(0), y_{n-1}(\delta)) - g_1(y_{n-1}(0), y_{n-1}(\delta))] \leq 0, \\
 p(T) &= y_{n-1}(T) - \tilde{y}(T) + \frac{1}{b}[g_2(\tilde{y}(T), \tilde{y}(\gamma)) - g_2(y_{n-1}(T), y_{n-1}(\gamma))]
 \end{aligned}$$

$$\leq y_{n-1}(T) - \tilde{y}(T) + \frac{1}{b} [g_2(\tilde{y}(T), y_{n-1}(\gamma)) - g_2(y_{n-1}(T), y_{n-1}(\gamma))] \leq 0.$$

This and assumption H_7 yield

$$\begin{aligned} p''(t) &= (Qy_{n-1})(t) + M(t)[y_n(t) - y_{n-1}(t)] + (\mathcal{L}(y_n - y_{n-1}))(t) - (Q\tilde{y})(t) \\ &\geq -M(t)[\tilde{y}(t) - y_{n-1}(t)] - (\mathcal{L}(\tilde{y} - y_{n-1}))(t) + M(t)[y_n(t) - y_{n-1}(t)] \\ &\quad + (\mathcal{L}(y_n - y_{n-1}))(t) = M(t)p(t) + (\mathcal{L}p)(t). \end{aligned}$$

By a similar way we can show that

$$q(0) \leq 0, \quad q(T) \leq 0 \quad \text{and} \quad q''(t) \geq M(t)q(t) + (\mathcal{L}q)(t).$$

By Lemma 1, $y_n(t) \leq \tilde{y}(t) \leq z_n(t)$, $t \in J$. If $n \rightarrow \infty$, it yields $y_0(t) \leq \bar{y}(t) \leq \tilde{y}(t) \leq \bar{z}(t) \leq z_0(t)$, $t \in J$. It proves that \bar{y}, \bar{z} are extremal solutions of problem (1) in the segment $[y_0, z_0]_*$. This ends the proof. \square

Now we investigate the case when problem (1) has the unique solution but first we need the following

Lemma 2. Assume that

- H_9 : $\delta, \gamma \in (0, T)$ and $0 \leq k\gamma < T, l \geq 0$,
- H_{10} : (i) $l \in (0, 1), k = 1$ or (ii) $l = 0, k \geq 0$.

Let $p \in C^2(J, \mathbb{R}), B \in C(J \times E, \mathbb{R})$ and

$$\begin{cases} p''(t) \geq B(t, p), & t \in J, \\ p(0) \leq lp(\delta), & p(T) \leq kp(\gamma). \end{cases} \tag{6}$$

Then function p satisfies the following inequality

$$\begin{aligned} p(t) &\leq \frac{1}{\Delta} \left\{ (T - k\gamma)l \int_0^\delta \left(\int_0^s B(\tau, p) d\tau \right) ds \right. \\ &\quad \left. + l\delta \left[- \int_0^T \left(\int_0^s B(\tau, p) d\tau \right) ds + k \int_0^\gamma \left(\int_0^s B(\tau, p) d\tau \right) ds \right] \right. \\ &\quad \left. + t(1 - l) \left[- \int_0^T \left(\int_0^s B(\tau, p) d\tau \right) ds + k \int_0^\gamma \left(\int_0^s B(\tau, p) d\tau \right) ds \right] \right. \\ &\quad \left. - t(1 - k)l \int_0^\delta \left(\int_0^s B(\tau, p) d\tau \right) ds \right\} + \int_0^t \left(\int_0^s B(\tau, p) d\tau \right) ds, \end{aligned}$$

where $\Delta = (1 - l)(T - k\gamma) + l\delta(1 - k)$.

Proof. We replace problem (6) by

$$\begin{cases} p''(t) = B(t, p) + A, & t \in J, \\ p(0) = lp(\delta) + a, & p(T) = kp(\gamma) + b \end{cases}$$

with $A \geq 0, a \leq 0, b \leq 0$. Integrating it two times on $[0, T]$, we have

$$p(t) = p(0) + p'(0)t + \frac{1}{2}At^2 + D(t), \quad t \in J, \tag{7}$$

where $D(t) = \int_0^t (\int_0^s B(\tau, p) d\tau) ds$.

Using the boundary conditions, we have the system

$$\begin{cases} (1-l)p(0) - l\delta p'(0) = a + l\left(\frac{1}{2}A\delta^2 + D(\delta)\right), \\ (1-k)p(0) + (T - k\gamma)p'(0) = b - \frac{1}{2}AT^2 - D(T) + k\left(\frac{1}{2}A\gamma^2 + D(\gamma)\right), \end{cases} \tag{8}$$

for finding $p(0)$ and $p'(0)$. Solving system (8) and substituting the solutions in formula (7) we obtain

$$p(t) = aa_1(t) + bb_1(t) + \frac{1}{2}A[c_1 + d_1(t)] + h_1(t),$$

where

$$\begin{aligned} a_1(t) &= \frac{1}{\Delta}[T - k\gamma + t(k - 1)], & b_1(t) &= \frac{1}{\Delta}[l\delta + t(1 - l)], \\ c_1 &= \frac{1}{\Delta}l\delta[\delta(T - k\gamma) - T^2 + k\gamma^2], \\ d_1(t) &= \frac{1}{\Delta}t[(1 - l)(-T^2 + k\gamma^2) - (1 - k)l\delta^2] + t^2, \\ h_1(t) &= \frac{1}{\Delta}[(T - k\gamma)lD(\delta) + l\delta(-D(T) + kD(\gamma)) + t(1 - l)(-D(T) + kD(\gamma)) \\ &\quad - t(1 - k)lD(\delta)] + D(t). \end{aligned}$$

Assume that $l \in (0, 1), k = 1$. Then $\Delta > 0, a_1(t) > 0, b_1(t) > 0$ and

$$\begin{aligned} c_1 &\leq \frac{1}{\Delta}l\delta[T(T - \gamma) - T^2 + \gamma^2] = \frac{1}{\Delta}l\delta\gamma(\gamma - T) < 0, \\ d_1(t) &= \frac{1}{\Delta}t(1 - l)(-T^2 + \gamma^2) + t^2 \leq \frac{1}{\Delta}t(1 - l)(-T^2 + T\gamma) + t^2 = t(t - T) \leq 0. \end{aligned}$$

This and (7) give $p(t) \leq h_1(t)$ because $A \geq 0, a \leq 0, b \leq 0$. The case (ii) can be discussed in the same way as above. It ends the proof. \square

Theorem 3. Assume that all assumptions of Theorem 2 and H_9, H_{10} are satisfied. In addition, we assume that

H_{11} : there exist a function $L \in C(J, \mathbb{R}_+)$ and a positive linear operator $\mathcal{L}_1 \in C(E, E)$ such that

$$(Q\bar{u})(t) - (Qu)(t) \geq -L_1(t)[\bar{u}(t) - u(t)] - (\mathcal{L}_1(\bar{u} - u))(t)$$

for $y_0(t) \leq u(t) \leq \bar{u}(t) \leq z_0(t)$,

H_{12} : there exist constants $0 < M_1 \leq a, 0 < M_2 \leq b, N_i \geq 0, i = 1, 2$, such that

$$\begin{aligned} g_1(\bar{u}, \bar{v}) - g_1(u, v) &\geq M_1(\bar{u} - u) - N_1(\bar{v} - v), \\ g_2(\bar{u}_1, \bar{v}_1) - g_2(u_1, v_1) &\geq M_2(\bar{u}_1 - u_1) - N_2(\bar{v}_1 - v_1) \end{aligned}$$

for $y_0(0) \leq u \leq \bar{u} \leq z_0(0)$, $y_0(\delta) \leq v \leq \bar{v} \leq z_0(\delta)$, $y_0(T) \leq u_1 \leq \bar{u}_1 \leq z_0(T)$, $y_0(\gamma) \leq v_1 \leq \bar{v}_1 \leq z_0(\gamma)$

and

$$\frac{1}{\Delta} [l\delta + T(1-l)] \int_0^T \left(\int_0^s [L_1(\tau) + (\mathcal{L}_1 \mathbf{1})(\tau)] d\tau \right) ds < 1 \quad (9)$$

with $l = \frac{N_1}{M_1}$, $k = \frac{N_2}{M_2}$, $\Delta = (1-l)(T - k\gamma) + l\delta(1-k)$.

Then problem (1) has, in the sector $[y_0, z_0]_*$, the unique solution.

Proof. Theorem 2 says that problem (1) has, in the sector $[y_0, z_0]_*$, extremal solutions \bar{y} , \bar{z} and $y_0(t) \leq \bar{y}(t) \leq \bar{z}(t) \leq z_0(t)$, $t \in J$. We want to show that $\bar{z} = \bar{y}$. Put $p = \bar{z} - \bar{y}$, so $p(t) \geq 0$, $t \in J$. In view of assumption H_{12} , we get

$$\begin{aligned} 0 &= g_1(\bar{z}(0), \bar{z}(\delta)) - g_1(\bar{y}(0), \bar{y}(\delta)) \geq M_1[\bar{z}(0) - \bar{y}(0)] - N_1[\bar{z}(\delta) - \bar{y}(\delta)] \\ &= M_1 p(0) - N_1 p(\delta), \\ 0 &= g_2(\bar{z}(T), \bar{z}(\gamma)) - g_2(\bar{y}(T), \bar{y}(\gamma)) \geq M_2[\bar{z}(T) - \bar{y}(T)] - N_2[\bar{z}(\gamma) - \bar{y}(\gamma)] \\ &= M_2 p(T) - N_2 p(\gamma), \end{aligned}$$

so

$$p(0) \leq lp(\delta), \quad p(T) \leq kp(\gamma).$$

Moreover, in view of assumption H_{11} , we see that

$$p''(t) = (Q\bar{z})(t) - (Q\bar{y})(t) \geq -L_1(t)p(t) - (\mathcal{L}_1 p)(t) \equiv B(t, p).$$

It is obvious that $B(t, p) \leq 0$, $t \in J$. From Lemma 2, we obtain

$$p(t) \leq \frac{1}{\Delta} \left\{ -l\delta \int_0^T \left(\int_0^s B(\tau, p) d\tau \right) ds - t(1-l) \int_0^T \left(\int_0^s B(\tau, p) d\tau \right) ds \right\}. \quad (10)$$

Suppose that $\max_{t \in J} p(t) = p(t_1) = d > 0$. Then $-B(t, p) \leq d[L_1(t) + (\mathcal{L}_1 \mathbf{1})(t)]$. From (10), we have now

$$\begin{aligned} d &\leq \frac{d}{\Delta} [l\delta + t_1(1-l)] \int_0^T \left(\int_0^s [L_1(\tau) + (\mathcal{L}_1 \mathbf{1})(\tau)] d\tau \right) ds \\ &\leq \frac{d}{\Delta} [l\delta + T(1-l)] \int_0^T \left(\int_0^s [L_1(\tau) + (\mathcal{L}_1 \mathbf{1})(\tau)] d\tau \right) ds, \end{aligned}$$

so

$$d \left\{ 1 - \frac{1}{\Delta} [l\delta + T(1-l)] \int_0^T \left(\int_0^s [L_1(\tau) + (\mathcal{L}_1 \mathbf{1})(\tau)] d\tau \right) ds \right\} \leq 0.$$

Hence $d \leq 0$, by condition (9), so $p(t) = 0$, $t \in J$. It proves that problem (1) has the unique solution. It ends the proof. \square



Example. Consider the problem

$$\begin{cases} x''(t) = (Qx)(t), & t \in [0, T], \\ 0 = x(0) - \frac{1}{3}x^2\left(\frac{1}{2}T\right) \equiv g_1\left(x(0), x\left(\frac{1}{2}T\right)\right), \\ 0 = x(T) - x\left(\frac{1}{3}T\right) \equiv g_2\left(x(T), x\left(\frac{1}{3}T\right)\right), \end{cases} \quad (11)$$

where

$$(Qx)(t) = -a_1 \cos x(t) - a_2(t)x(t) - b_1(t) \sin x\left(\frac{1}{4}t\right) + b_2(t)x\left(\frac{1}{3}t\right) - k_1.$$

Note that $\delta = \frac{1}{2}T$, $\gamma = \frac{1}{3}T$. Assume that $a_1 > 0$, $a_2, b_1, b_2 \in C(J, [0, \infty))$, $k_1 \geq 0$ and

$$-a_1 \cos 1 - a_2(t) - b_1(t) \sin 1 + b_2(t) - k_1 \geq 0, \quad (12)$$

$$\frac{a_1 T^2}{2} + \int_0^T \int_s^T [b_1(\tau) + b_2(\tau)] d\tau ds \leq 1, \quad (13)$$

$$\frac{a_1 T^2}{2} + \int_0^T \int_0^s a_2(\tau) d\tau ds < \frac{1}{3}. \quad (14)$$

Take $y_0(t) = 0$, $z_0(t) = 1$, $t \in J$. Then

$$(Qy_0)(t) = -a_1 - k_1 < 0 = y_0''(t),$$

$$(Qz_0)(t) = -a_1 \cos 1 - a_2(t) - b_1(t) \sin 1 + b_2(t) - k_1 \geq 0 = z_0''(t),$$

by (12). Moreover,

$$\begin{aligned} g_1\left(y_0(0), y_0\left(\frac{1}{2}T\right)\right) &= g_1(0, 0) = 0, & g_2\left(y_0(T), y_0\left(\frac{1}{3}T\right)\right) &= g_2(0, 0) = 0, \\ g_1\left(z_0(0), z_0\left(\frac{1}{2}T\right)\right) &= g_1(1, 1) = \frac{2}{3} > 0, & g_2\left(z_0(T), z_0\left(\frac{1}{3}T\right)\right) &= g_2(1, 1) = 0. \end{aligned}$$

This shows that y_0, z_0 are lower and upper solutions of problem (11), respectively. It is quite easy to see that assumptions H_7, H_8 hold with $a = b = 1$, $M(t) = a_1$ and $(\mathcal{L}u)(t) = b_1(t)u\left(\frac{1}{4}t\right) + b_2(t)u\left(\frac{1}{3}t\right)$. In view of (13), assumption H_3 holds. It proves that problem (11) has extremal solutions in the sector $[y_0, z_0]_*$, by Theorem 2.

Now we are going to show that all assumptions of Theorem 3 are satisfied. Note that $L_1(t) = a_1 + a_2(t)$, $(\mathcal{L}u)(t) = 0$, $t \in J$, and $M_1 = 1$, $N_1 = \frac{2}{3}$, $M_2 = N_2 = 1$, so $k = 1$, $l = \frac{2}{3} < 1$. Moreover, $\Delta = \frac{2}{3}T$ and assumption (9) holds, by (14). Hence, problem (11) has, in the sector $[y_0, z_0]_*$, the unique solution.

For example, we take $T = 1$, $k_1 = 0$, and

$$a_1 = \frac{1}{8 \cos 1}, \quad a_2(t) = \frac{1}{8} \sin t, \quad b_1(t) = \frac{\beta \sin t}{\sin 1}, \quad b_2(t) = \left(\frac{1}{8} + \beta\right) \sin t + \frac{1}{8}.$$

Then conditions (12)–(14) are satisfied with $\beta \leq 1.0143$.



4. Quasi-solutions. Unique solution

This section deals with the problem of existence of quasi-solutions for (1). The case when problem (1) has the unique solution is also investigated.

A pair of functions $y_0, z_0 \in C^2(J, \mathbb{R})$ is called weakly coupled (w.c.) lower and upper solutions of problem (1) if

$$\begin{cases} y_0''(t) \geq (Qy_0)(t), & t \in J, \\ 0 \geq g_1(y_0(0), z_0(\delta)), & 0 \geq g_2(y_0(T), z_0(\gamma)), \\ z_0''(t) \leq (Qz_0)(t), & t \in J, \\ 0 \leq g_1(z_0(0), y_0(\delta)), & 0 \leq g_2(z_0(T), y_0(\gamma)). \end{cases}$$

A pair (U, V) , $U, V \in C^2(J, \mathbb{R})$ is called a weakly coupled quasi-solution of problem (1) if

$$\begin{cases} U'(t) = (QU)(t), & t \in J, \\ 0 = g_1(U(0), V(\delta)), & 0 = g_2(U(T), V(\gamma)), \\ V'(t) = (QV)(t), & t \in J, \\ 0 = g_1(V(0), U(\delta)), & 0 = g_2(V(T), U(\gamma)). \end{cases}$$

A weakly coupled quasi-solution (\bar{U}, \bar{V}) , $\bar{U}, \bar{V} \in C^2(J, \mathbb{R})$ is called the weakly coupled minimal and maximal quasi-solution of problem (1) if for any weakly coupled quasi-solution (U, V) of (1) we have $\bar{U}(t) \leq U(t)$, $V(t) \leq \bar{V}(t)$ on J .

Theorem 4. Suppose that assumptions H_1 – H_4 , H_7 are satisfied. Let $y_0, z_0 \in C^2(J, \mathbb{R})$ be w.c. lower and upper solutions of problem (1), and $y_0(t) \leq z_0(t)$, $t \in J$. In addition, we assume that g_i , $i = 1, 2$ are nondecreasing with respect to the second variable and there exist positive constants a, b such that

$$\begin{aligned} g_1(\bar{u}, v) - g_1(u, v) &\leq a(\bar{u} - u), \\ g_2(\bar{u}_1, v_1) - g_2(u_1, v_1) &\leq b(\bar{u}_1 - u_1) \end{aligned}$$

for $y_0(0) \leq u \leq \bar{u} \leq z_0(0)$, $y_0(T) \leq u_1 \leq \bar{u}_1 \leq z_0(T)$, $y_0(\delta) \leq v \leq z_0(\delta)$, $y_0(\gamma) \leq v_1 \leq z_0(\gamma)$.

Then problem (1) has, in the sector $[y_0, z_0]_*$ the w.c. minimal and maximal quasi-solutions.

Proof. Let us define two sequences $\{y_n, z_n\}$ by relations:

$$\begin{cases} y_n''(t) = (Qy_{n-1})(t) + M(t)[y_n(t) - y_{n-1}(t)] + (\mathcal{L}(y_n - y_{n-1}))(t), & t \in J, \\ y_n(0) = -\frac{1}{a}g_1(y_{n-1}(0), z_{n-1}(\delta)) + y_{n-1}(0), \\ y_n(T) = -\frac{1}{b}g_2(y_{n-1}(T), z_{n-1}(\gamma)) + y_{n-1}(T), \end{cases}$$

$$\begin{cases} z_n''(t) = (Qz_{n-1})(t) + M(t)[z_n(t) - z_{n-1}(t)] + (\mathcal{L}(z_n - z_{n-1}))(t), & t \in J, \\ z_n(0) = -\frac{1}{a}g_1(z_{n-1}(0), y_{n-1}(\delta)) + z_{n-1}(0), \\ z_n(T) = -\frac{1}{b}g_2(z_{n-1}(T), y_{n-1}(\gamma)) + z_{n-1}(T) \end{cases}$$

for $n = 1, 2, \dots$. The proof is similar to the proof of Theorem 2 and therefore it is omitted. \square

Theorem 5. Assume that all assumptions of Theorem 4 and H_9 – H_{11} are satisfied. In addition, we assume that:

H'_{12} : there exist constants $0 < M_1 \leq a$, $0 < M_2 \leq b$, $N_i \geq 0$, $i = 1, 2$, such that

$$g_1(\bar{u}, v) - g_1(u, \bar{v}) \geq M_1(\bar{u} - u) - N_1(\bar{v} - v),$$

$$g_2(\bar{u}_1, v_1) - g_2(u_1, \bar{v}_1) \geq M_2(\bar{u}_1 - u_1) - N_2(\bar{v}_1 - v_1)$$

for $y_0(0) \leq u \leq \bar{u} \leq z_0(0)$, $y_0(\delta) \leq v \leq \bar{v} \leq z_0(\delta)$, $y_0(T) \leq u_1 \leq \bar{u}_1 \leq z_0(T)$, $y_0(\gamma) \leq v_1 \leq \bar{v}_1 \leq z_0(\gamma)$

and

$$\frac{1}{\Delta} [l\delta + T(1-l)] \int_0^T \left(\int_0^s [L_1(\tau) + (\mathcal{L}_1 \mathbf{1})(\tau)] d\tau \right) ds < 1$$

with $l = \frac{N_1}{M_1}$, $k = \frac{N_2}{M_2}$, $\Delta = (1-l)(T - k\gamma) + l\delta(1-k)$.

Then problem (1) has, in the sector $[y_0, z_0]_*$, the unique solution.

The proof of Theorem 5 is similar to the proof of Theorem 3 and therefore it is omitted.

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