NONMONOTONE IMPULSE EFFECTS IN SECOND-ORDER PERIODIC BOUNDARY VALUE PROBLEMS

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We deal with the nonlinear impulsive periodic boundary value problem $u'' = f(t,u,u')$, $u(t_i+) = J_i(u(t_i))$, $u'(t_i+) = M_i(u'(t_i))$, $i = 1,2,\dots,m$, $u(0) = u(T)$, $u'(0) = u'(T)$. We establish the existence results which rely on the presence of a well-ordered pair (σ_1,σ_2) of lower/upper functions ($\sigma_1 \le \sigma_2$ on $[0,T]$) associated with the problem. In contrast to previous papers investigating such problems, the monotonicity of the impulse functions J_i, M_i is not required here.

1. Introduction

In recent years, the theory of impulsive differential equations has become a well-respected branch of mathematics. This is because of its characteristic features which provide many interesting problems that cannot be solved by applying standard methods from the theory of ordinary differential equations. It can also give a natural description of many real models from applied sciences (see the examples mentioned in [1, 2]).

In particular, starting with [7], periodic boundary value problems for nonlinear second-order impulsive differential equations of the form (2.1), (2.2), and (2.3) have received considerable attention; see, e.g., [1, 3, 5, 6, 8, 9, 14], where the existence results in terms of lower and upper functions can also be found. However, all impose certain monotonicity requirements on the impulse functions. In contrast to these papers, we provide existence results using weaker conditions (2.10) and (2.11) instead of monotonicity.

Throughout the paper, we keep the following notation and conventions. For a real valued function u defined a.e. on $[0,T]$, we put

$$\|u\|_\infty = \sup_{t \in [0,T]} \mathrm{ess} \, |u(t)|, \qquad \|u\|_1 = \int_0^T |u(s)| \, ds. \tag{1.1}$$

For a given interval $J \subset \mathbb{R}$, let $\mathbb{C}(J)$ denote the set of real-valued functions which are continuous on J. Furthermore, let $\mathbb{C}^1(J)$ be the set of functions having continuous first derivatives on J, and $\mathbb{L}(J)$ the set of functions which are Lebesgue integrable on J.

Let $m \in \mathbb{N}$ and let

$$0 = t_0 < t_1 < t_2 < \cdots < t_m < t_{m+1} = T \tag{1.2}$$

be a division of the interval $[0, T]$. We denote

$$\mathrm{D} = \{t_1, t_2, \ldots, t_m\} \tag{1.3}$$

and define $\mathbb{C}_{\mathrm{D}}^1[0, T]$ as the set of functions $u : [0, T] \mapsto \mathbb{R}$,

$$u(t) = \begin{cases} u_{[0]}(t) & \text{if } t \in [0, t_1], \\ u_{[1]}(t) & \text{if } t \in (t_1, t_2], \\ \quad \vdots & \quad \vdots \\ u_{[m]}(t) & \text{if } t \in (t_m, T], \end{cases} \tag{1.4}$$

where $u_{[i]} \in \mathbb{C}^1[t_i, t_{i+1}]$ for $i = 0, 1, \ldots, m$. Moreover, $\mathbb{AC}_{\mathrm{D}}^1[0, T]$ stands for the set of functions $u \in \mathbb{C}_{\mathrm{D}}^1[0, T]$ having first derivatives absolutely continuous on each subinterval (t_i, t_{i+1}), $i = 0, 1, \ldots, m$. For $u \in \mathbb{C}_{\mathrm{D}}^1[0, T]$ and $i = 1, 2, \ldots, m+1$, we write

$$u'(t_i) = u'(t_i -) = \lim_{t \to t_i-} u'(t), \qquad u'(0) = u'(0+) = \lim_{t \to 0+} u'(t), \tag{1.5}$$

$$\|u\|_{\mathrm{D}} = \|u\|_{\infty} + \|u'\|_{\infty}. \tag{1.6}$$

Note that the set $\mathbb{C}_{\mathrm{D}}^1[0, T]$ becomes a Banach space when equipped with the norm $\| \cdot \|_{\mathrm{D}}$ and with the usual algebraic operations.

We say that $f : [0, T] \times \mathbb{R}^2 \mapsto \mathbb{R}$ satisfies the *Carathéodory conditions* on $[0, T] \times \mathbb{R}^2$ if

(i) for each $x \in \mathbb{R}$ and $y \in \mathbb{R}$, the function $f(\cdot, x, y)$ is measurable on $[0, T]$;

(ii) for a.e. $t \in [0, T]$, the function $f(t, \cdot, \cdot)$ is continuous on $\mathbb{R}^2$;

(iii) for each compact set $K \subset \mathbb{R}^2$, there is a function $m_K(t) \in \mathbb{L}[0, T]$ such that $|f(t, x, y)| \le m_K(t)$ holds for a.e. $t \in [0, T]$ and all $(x, y) \in K$.

The set of functions satisfying the Carathéodory conditions on $[0, T] \times \mathbb{R}^2$ will be denoted by $\mathrm{Car}([0, T] \times \mathbb{R}^2)$.

Given a Banach space $\mathbb{X}$ and its subset M, let $\mathrm{cl}(M)$ and ∂M denote the closure and the boundary of M, respectively.

Let Ω be an open bounded subset of $\mathbb{X}$. Assume that the operator $\mathrm{F} : \mathrm{cl}(\Omega) \mapsto \mathbb{X}$ is completely continuous and $\mathrm{F}u \ne u$ for all $u \in \partial \Omega$. Then $\deg(\mathrm{I} - \mathrm{F}, \Omega)$ denotes the *Leray-Schauder topological degree* of $\mathrm{I} - \mathrm{F}$ with respect to Ω, where I is the identity operator on $\mathbb{X}$. For a definition and properties of the degree, see, for example, [4] or [10].

2. Formulation of the problem and main assumptions

Here we study the existence of solutions to the following problem:

$$u'' = f(t, u, u'), \tag{2.1}$$

$$u(t_i+) = \mathrm{J}_i(u(t_i)), \quad u'(t_i+) = \mathrm{M}_i(u'(t_i)), \quad i = 1, 2, \ldots, m, \tag{2.2}$$

$$u(0) = u(T), \qquad u'(0) = u'(T), \tag{2.3}$$

where $u'(t_i)$ are understood in the sense of (1.5), $f \in \text{Car}([0,T] \times \mathbb{R}^2)$, $J_i \in \mathbb{C}(\mathbb{R})$, and $M_i \in \mathbb{C}(\mathbb{R})$.

Definition 2.1. A *solution of the problem* (2.1), (2.2), and (2.3) is a function $u \in \mathbb{AC}_D^1[0,T]$ which satisfies the impulsive conditions (2.2), the periodic conditions (2.3), and for a.e. $t \in [0,T]$ fulfils the equation $u''(t) = f(t,u(t),u'(t))$.

Definition 2.2. A function $\sigma_1 \in \mathbb{AC}_D^1[0,T]$ is called a *lower function of problem* (2.1), (2.2), and (2.3) if

$$\sigma_1''(t) \geq f(t,\sigma_1(t),\sigma_1'(t)) \quad \text{for a.e. } t \in [0,T],$$
$$\sigma_1(t_i+) = J_i(\sigma_1(t_i)), \quad \sigma_1'(t_i+) \geq M_i(\sigma_1'(t_i)), \quad i = 1,2,\ldots,m, \qquad (2.4)$$
$$\sigma_1(0) = \sigma_1(T), \qquad \sigma_1'(0) \geq \sigma_1'(T).$$

Similarly, a function $\sigma_2 \in \mathbb{AC}_D^1[0,T]$ is an *upper function of problem* (2.1), (2.2), and (2.3) if

$$\sigma_2''(t) \leq f(t,\sigma_2(t),\sigma_2'(t)) \quad \text{for a.e. } t \in [0,T], \qquad (2.5)$$
$$\sigma_2(t_i+) = J_i(\sigma_2(t_i)), \quad \sigma_2'(t_i+) \leq M_i(\sigma_2'(t_i)), \quad i = 1,2,\ldots,m, \qquad (2.6)$$
$$\sigma_2(0) = \sigma_2(T), \qquad \sigma_2'(0) \leq \sigma_2'(T). \qquad (2.7)$$

Throughout the paper we assume

$$0 = t_0 < t_1 < t_2 < \cdots < t_m < t_{m+1} = T < \infty, \qquad D = \{t_1,t_2,\ldots,t_m\},$$
$$f \in \text{Car}([0,T] \times \mathbb{R}^2), \qquad J_i \in \mathbb{C}(\mathbb{R}), \qquad M_i \in \mathbb{C}(\mathbb{R}), \quad i = 1,2,\ldots,m; \qquad (2.8)$$

σ_1 and σ_2 are, respectively, lower and upper functions of (2.1), (2.2), and (2.3),
$$\sigma_1 \leq \sigma_2 \text{ on } [0,T]; \qquad (2.9)$$

$$\sigma_1(t_i) \leq x \leq \sigma_2(t_i) \implies J_i(\sigma_1(t_i)) \leq J_i(x) \leq J_i(\sigma_2(t_i)), \quad i = 1,2,\ldots,m; \qquad (2.10)$$

$$y \leq \sigma_1'(t_i) \implies M_i(y) \leq M_i(\sigma_1'(t_i)),$$
$$y \geq \sigma_2'(t_i) \implies M_i(y) \geq M_i(\sigma_2'(t_i)), \quad i = 1,2,\ldots,m. \qquad (2.11)$$

Remark 2.3. If $M_i(0) = 0$ for $i = 1,2,\ldots,m$ and $r_1 \in \mathbb{R}$ is such that $J_i(r_1) = r_1$ for $i = 1,2,\ldots,m$ and

$$f(t,r_1,0) \leq 0 \quad \text{for a.e. } t \in [0,T], \qquad (2.12)$$

then $\sigma_1(t) \equiv r_1$ on $[0,T]$ is a lower function of problem (2.1), (2.2), and (2.3). Similarly, if $r_2 \in \mathbb{R}$ is such that $J_i(r_2) = r_2$ for all $i = 1,2,\ldots,m$ and

$$f(t,r_2,0) \geq 0 \quad \text{for a.e. } t \in [0,T], \qquad (2.13)$$

then $\sigma_2(t) \equiv r_2$ is an upper function of problem (2.1), (2.2), and (2.3).

3. A priori estimates

At the beginning of this section, we introduce a class of auxiliary problems and prove uniform a priori estimates for their solutions.

Take $d \in \mathbb{R}$, $\widetilde{f} \in \mathrm{Car}([0,T] \times \mathbb{R}^2)$, $\widetilde{J}_i \in \mathbb{C}(\mathbb{R})$, and $\widetilde{M}_i \in \mathbb{C}(\mathbb{R})$, $i = 1,2,\dots,m$, such that

$$\widetilde{f}(t,x,y) < f(t,\sigma_1(t),\sigma_1'(t)) \quad \text{for a.e. } t \in [0,T], \text{ all } x \in (-\infty,\sigma_1(t)),$$

$$\text{and all } y \in \mathbb{R} \text{ such that } |y - \sigma_1'(t)| \leq \frac{\sigma_1(t) - x}{\sigma_1(t) - x + 1};$$

$$\widetilde{f}(t,x,y) > f(t,\sigma_2(t),\sigma_2'(t)) \quad \text{for a.e. } t \in [0,T], \text{ all } x \in (\sigma_2(t),\infty),$$

$$\text{and all } y \in \mathbb{R} \text{ such that } |y - \sigma_2'(t)| \leq \frac{x - \sigma_2(t)}{x - \sigma_2(t) + 1};$$

$$(3.1)$$

$$\begin{aligned}
\widetilde{J}_i(x) &< J_i(\sigma_1(t_i)) &&\text{if } x < \sigma_1(t_i), \\
\widetilde{J}_i(x) &= J_i(x) &&\text{if } x \in [\sigma_1(t_i),\sigma_2(t_i)], \quad (i = 1,2,\dots,m); \\
\widetilde{J}_i(x) &> J_i(\sigma_2(t_i)) &&\text{if } x > \sigma_2(t_i),
\end{aligned} \quad (3.2)$$

$$\begin{aligned}
\widetilde{M}_i(y) &\leq M_i(\sigma_1'(t_i)) &&\text{if } y \leq \sigma_1'(t_i), \\
\widetilde{M}_i(y) &\geq M_i(\sigma_2'(t_i)) &&\text{if } y \geq \sigma_2'(t_i),
\end{aligned} \quad (i = 1,2,\dots,m); \quad (3.3)$$

$$\sigma_1(0) \leq d \leq \sigma_2(0), \quad (3.4)$$

and consider an auxiliary Dirichlet problem

$$u'' = \widetilde{f}(t,u,u'), \quad (3.5)$$

$$u(t_i+) = \widetilde{J}_i(u(t_i)), \quad u'(t_i+) = \widetilde{M}_i(u'(t_i)), \quad i = 1,2,\dots,m, \quad (3.6)$$

$$u(0) = u(T) = d. \quad (3.7)$$

LEMMA 3.1. *Let (2.8), (2.9), and (2.10) and (3.1), (3.2), (3.3), and (3.4) hold. Then every solution u of (3.5), (3.6), and (3.7) satisfies*

$$\sigma_1 \leq u \leq \sigma_2 \quad \text{on } [0,T]. \quad (3.8)$$

Proof. Let u be a solution of (3.5), (3.6), and (3.7). Put $v(t) = u(t) - \sigma_2(t)$ for $t \in [0,T]$. Then, by (3.4), we have

$$v(0) = v(T) \leq 0. \quad (3.9)$$

So, it remains to prove that $v \leq 0$ on $(0,T)$.

Part (i). First, we show that v does not have a positive local maximum at any point of $(0,T) \setminus D$. Assume, on the contrary, that there is $\alpha \in (0,T) \setminus D$ such that v has a positive local maximum at α, that is,

$$v(\alpha) > 0, \qquad v'(\alpha) = 0. \quad (3.10)$$

This guarantees the existence of β such that $[\alpha, \beta] \subset (0, T) \setminus D$ and

$$v(t) > 0, \qquad |v'(t)| < \frac{v(t)}{v(t)+1} < 1 \tag{3.11}$$

for $t \in [\alpha, \beta]$. Using (2.5), (3.1), and (3.11), we get

$$\begin{aligned}v''(t) &= u''(t) - \sigma_2''(t) = \widetilde{f}(t, u(t), u'(t)) - \sigma_2''(t) \\ &> f(t, \sigma_2(t), \sigma_2'(t)) - \sigma_2''(t) \geq 0\end{aligned} \tag{3.12}$$

for a.e. $t \in [\alpha, \beta]$. Hence,

$$0 < \int_\alpha^t v''(s)\,ds = v'(t) \tag{3.13}$$

for all $t \in (\alpha, \beta]$. This contradicts that v has a local maximum at α.

Part (ii). Now, assume that there is $t_j \in D$ such that

$$\max_{t \in (t_{j-1}, t_j]} v(t) = v(t_j) > 0. \tag{3.14}$$

Then $v'(t_j) \geq 0$. By (3.2) and (3.3), we get

$$\widetilde{J}_j(u(t_j)) > J_j(\sigma_2(t_j)), \qquad \widetilde{M}_j(u'(t_j)) \geq M_j(\sigma_2'(t_j)). \tag{3.15}$$

By (3.6) and (2.6), the relations

$$v(t_j+) > 0, \qquad v'(t_j+) \geq 0 \tag{3.16}$$

follow. If $v'(t_j+) > 0$, then there is $\beta \in (t_j, t_{j+1})$ such that

$$v'(t) > 0 \quad \text{on } (t_j, \beta]. \tag{3.17}$$

If $v'(t_j+) = 0$, then we can find β such that $(t_j, \beta] \subset (0, T) \setminus D$ and (3.11) is satisfied on $(t_j, \beta]$. Consequently, (3.17) is valid in this case as well. As by Part (i) v' cannot change its sign on (t_j, t_{j+1}), in both these cases we have

$$v'(t) \geq 0 \quad \text{on } (t_j, t_{j+1}). \tag{3.18}$$

Now, by (3.16), (3.17), and (3.18), we get

$$\max_{t \in (t_j, t_{j+1}]} v(t) = v(t_{j+1}) > 0. \tag{3.19}$$

Continuing inductively, we get $v(T) > 0$ contrary to (3.9).

Part (iii). Finally, assume that

$$\sup_{t \in (t_j, t_{j+1}]} v(t) = v(t_j +) > 0 \tag{3.20}$$

for some $t_j \in D$. In view of (3.2), this is possible only if

$$\widetilde{J}_j(u(t_j)) > J_j(\sigma_2(t_j)). \tag{3.21}$$

If $u(t_j) \in [\sigma_1(t_j), \sigma_2(t_j)]$, then by (3.2) and (2.10), we have

$$\widetilde{J}_j(u(t_j)) = J_j(u(t_j)) \le J_j(\sigma_2(t_j)), \tag{3.22}$$

contrary to (3.21). If $u(t_j) < \sigma_1(t_j)$, then by (3.2), (2.9), and (2.10), we get

$$\widetilde{J}_j(u(t_j)) < J_j(\sigma_1(t_j)) \le J_j(\sigma_2(t_j)), \tag{3.23}$$

again a contradiction to (3.21). Therefore, $u(t_j) > \sigma_2(t_j)$, that is, $v(t_j) > 0$. Further, (3.20) gives $v'(t_j+) \le 0$. If $v'(t_j+) = 0$, then, as in Part (ii), we get (3.17), which contradicts (3.20). Therefore, $v'(t_j+) < 0$, which yields, with (3.3), that $v'(t_j) < 0$. Thus, in view of Part (i), we deduce that $v' \le 0$ on (t_{j-1}, t_j), that is, $\sup_{t \in (t_{j-1}, t_j]} v(t) = v(t_{j-1}+) > 0$. Continuing inductively, we get $v(0) > 0$, contradicting (3.9).

To summarize, we have proved that $v \le 0$ on $[0, T]$ which means that $u \le \sigma_2$ on $[0, T]$. If we put $v = \sigma_1 - u$ on $[0, T]$ and use the properties of σ_1 instead of σ_2, we can prove $\sigma_1 \le u$ on $[0, T]$ by an analogous argument. $\qquad \square$

In the proof of Theorem 4.1, we need a priori estimates for derivatives of solutions. To this aim we prove the following lemma.

LEMMA 3.2. *Assume that $r \in (0, \infty)$ and that*

$$h \in \mathbb{L}[0, T] \quad \text{is nonnegative a.e. on } [0, T], \tag{3.24}$$

$$\omega \in \mathbb{C}([1, \infty)) \quad \text{is positive on } [1, \infty), \quad \int_1^\infty \frac{ds}{\omega(s)} = \infty. \tag{3.25}$$

Then there exists $r^* \in (1, \infty)$ such that the estimate

$$\|u'\|_\infty \le r^* \tag{3.26}$$

holds for each function $u \in \mathbb{AC}_D^1[0, T]$ satisfying $\|u\|_\infty \le r$ and

$$|u''(t)| \le \omega(|u'(t)|)(|u'(t)| + h(t)) \quad \text{for a.e. } t \in [0, T], \text{ for } |u'(t)| > 1. \tag{3.27}$$

Proof. Let $u \in \mathbb{AC}_D^1[0, T]$ satisfy (3.27) and let $\|u\|_\infty \le r$. The mean value theorem implies that there are $\xi_i \in (t_i, t_{i+1})$ such that

$$|u'(\xi_i)| < \frac{2r}{\Delta} + 1, \quad i = 1, 2, \dots, m, \tag{3.28}$$

where

$$\Delta = \min_{i=0,1,\dots,m} (t_{i+1} - t_i). \tag{3.29}$$

Put

$$c_0 = \frac{2r}{\Delta} + 1, \qquad \rho = \|u'\|_\infty. \tag{3.30}$$

By replacing u by $-u$ if necessary, we may assume that $\rho > c_0$ and

$$\rho = \sup_{t \in (t_j, t_{j+1}]} u'(t) \quad \text{for some } j \in \{0, 1, \dots, m\}. \tag{3.31}$$

Thus we have

$$\rho = u'(\alpha) \quad \text{for some } \alpha \in (t_j, t_{j+1}] \tag{3.32}$$

or

$$\rho = u'(\alpha+) \quad \text{with} \quad \alpha = t_j. \tag{3.33}$$

By (3.28), there is $\beta \in (t_j, t_{j+1})$, $\beta \neq \alpha$, such that $u'(\beta) = c_0$ and $u'(t) \geq c_0$ for all t lying between α and β. Assume that (3.32) occurs. There are two cases to consider: $t_j < \beta < \alpha \leq t_{j+1}$ or $t_j < \alpha < \beta < t_{j+1}$.

Case 1. Let $t_j < \beta < \alpha \leq t_{j+1}$. Since $u'(t) > 1$ on $[\beta, \alpha]$, (3.27) gives

$$u''(t) \leq \omega(u'(t))(u'(t) + h(t)) \quad \text{for a.e. } t \in [\beta, \alpha], \tag{3.34}$$

and hence

$$\int_{c_0}^{\rho} \frac{ds}{\omega(s)} = \int_{\beta}^{\alpha} \frac{u''(t)}{\omega(u'(t))} dt \leq \int_{\beta}^{\alpha} u'(t) dt + \|h\|_1 \leq 2r + \|h\|_1. \tag{3.35}$$

On the other hand, by (3.25), there is $r^* > c_0$ such that

$$\int_{c_0}^{r^*} \frac{ds}{\omega(s)} > 2r + \|h\|_1, \tag{3.36}$$

which is possible only if $\rho < r^*$, that is, if (3.26) holds.

Case 2. Let $t_j < \alpha < \beta < t_{j+1}$. By (3.27), we get

$$-u''(t) \leq \omega(u'(t))(u'(t) + h(t)) \quad \text{for a.e. } t \in [\alpha, \beta],$$

$$\int_{c_0}^{\rho} \frac{ds}{\omega(s)} = -\int_{\alpha}^{\beta} \frac{u''(t)}{\omega(u'(t))} dt \leq 2r + \|h\|_1, \tag{3.37}$$

so the inequality (3.26) follows.

If (3.33) occurs, a similar argument to that in Case 2 applies and gives (3.26) as well.

$\square$

Remark 3.3. Notice that the condition

$$\int_1^\infty \frac{ds}{\omega(s)} = \infty \tag{3.38}$$

in (3.25) can be weakened. In particular, the estimate (3.26) holds whenever $r^* \in (0, \infty)$ is such that

$$\int_{c_0}^{r^*} \frac{ds}{\omega(s)} > 2r + \|h\|_1. \tag{3.39}$$

4. Main results

The main existence result for problem (2.1), (2.2), and (2.3) is provided by the following theorem.

THEOREM 4.1. *Assume that (2.8), (2.9), (2.10), and (2.11) hold. Further, let*

$$|f(t,x,y)| \le \omega(|y|)(|y| + h(t)) \quad \text{for a.e. } t \in [0,T] \text{ and all } x \in [\sigma_1(t), \sigma_2(t)], |y| > 1, \tag{4.1}$$

where h and ω fulfil (3.24) and (3.25). Then the problem (2.1), (2.2), and (2.3) has a solution u satisfying (3.8).

Before proving this theorem, we prove the next key proposition where we restrict ourselves to the case that f is bounded by a Lebesgue integrable function.

PROPOSITION 4.2. *Assume that (2.8), (2.9), (2.10), and (2.11) hold. Further, let $m \in \mathbb{L}[0,T]$ be such that*

$$|f(t,x,y)| \le m(t) \quad \text{for a.e. } t \in [0,T] \text{ and all } (x,y) \in [\sigma_1(t), \sigma_2(t)] \times \mathbb{R}. \tag{4.2}$$

Then the problem (2.1), (2.2), and (2.3) has a solution u fulfilling (3.8).

Proof
Step 1. We construct a proper auxiliary problem.
    Let Δ be given by (3.29). Put

$$c = \|m\|_1 + \frac{\|\sigma_1\|_\infty + \|\sigma_2\|_\infty}{\Delta} + \|\sigma_1'\|_\infty + \|\sigma_2'\|_\infty, \tag{4.3}$$

and for $t \in [0,T]$ and $(x,y) \in \mathbb{R}^2$, define

$$\alpha(t,x) = \begin{cases} \sigma_1(t) & \text{if } x < \sigma_1(t), \\ x & \text{if } \sigma_1(t) \le x \le \sigma_2(t), \\ \sigma_2(t) & \text{if } x > \sigma_2(t), \end{cases} \tag{4.4}$$

$$\beta(y) = \begin{cases} y & \text{if } |y| \le c, \\ c \, \mathrm{sgn}\, y & \text{if } |y| > c. \end{cases} \tag{4.5}$$

For a.e. $t \in [0, T]$ and all $(x, y) \in \mathbb{R}^2$, $\varepsilon \in [0, 1]$, define functions

$$\omega_k(t, \varepsilon) = \sup_{y \in [\sigma'_k(t) - \varepsilon, \sigma'_k(t) + \varepsilon]} | f(t, \sigma_k(t), \sigma'_k(t)) - f(t, \sigma_k(t), y) |, \quad k = 1, 2, \tag{4.6}$$

$$\begin{aligned} \widetilde{J}_i(x) &= x + J_i(\alpha(t_i, x)) - \alpha(t_i, x), \\ \widetilde{M}_i(y) &= y + M_i(\beta(y)) - \beta(y), \end{aligned} \qquad i = 1, 2, \dots, m, \tag{4.7}$$

$$\widetilde{f}(t, x, y) = \begin{cases} f(t, \sigma_1(t), y) - \omega_1\left(t, \dfrac{\sigma_1(t) - x}{\sigma_1(t) - x + 1}\right) - \dfrac{\sigma_1(t) - x}{\sigma_1(t) - x + 1} & \text{if } x < \sigma_1(t), \\[2mm] f(t, x, y) & \text{if } \sigma_1(t) \le x \le \sigma_2(t), \\[2mm] f(t, \sigma_2(t), y) + \omega_2\left(t, \dfrac{x - \sigma_2(t)}{x - \sigma_2(t) + 1}\right) + \dfrac{x - \sigma_2(t)}{x - \sigma_2(t) + 1} & \text{if } x > \sigma_2(t). \end{cases} \tag{4.8}$$

We see that $\omega_k \in \mathrm{Car}([0, T] \times [0, 1])$ are nonnegative and nondecreasing in the second variable and $\omega_k(0) = 0$ for $k = 1, 2$. Consequently, $\widetilde{f} \in \mathrm{Car}([0, T] \times \mathbb{R}^2)$. Furthermore, $\widetilde{J}_i$, $\widetilde{M}_i \in \mathbb{C}(\mathbb{R})$, $i = 1, 2, \dots, m$. The auxiliary problem is (3.5), (3.6), and

$$u(0) = u(T) = \alpha(0, u(0) + u'(0) - u'(T)). \tag{4.9}$$

Step 2. We prove that problem (3.5), (3.6), (4.9) *is solvable.*

Let

$$G(t, s) = \begin{cases} \dfrac{t(s - T)}{T} & \text{if } 0 \le t \le s \le T, \\[3mm] \dfrac{s(t - T)}{T} & \text{if } 0 \le s < t \le T, \end{cases}$$

$$G_1(t, s) = \begin{cases} -\dfrac{t}{T} & \text{if } 0 \le t \le s \le T, \\[3mm] \dfrac{T - t}{T} & \text{if } 0 \le s < t \le T. \end{cases} \tag{4.10}$$

Define an operator $\widetilde{F} : \mathbb{C}^1_D[0, T] \mapsto \mathbb{C}^1_D[0, T]$ by

$$\begin{aligned} (\widetilde{F}u)(t) = {}& \alpha(0, u(0) + u'(0) - u'(T)) + \int_0^T G(t, s) \widetilde{f}(s, u(s), u'(s)) \, ds \\ & + \sum_{i=1}^m G_1(t, t_i) \left(\widetilde{J}_i(u(t_i)) - u(t_i) \right) + \sum_{i=1}^m G(t, t_i) \left(\widetilde{M}_i(u'(t_i)) - u'(t_i) \right). \end{aligned} \tag{4.11}$$

As in [13, Lemma 3.1], we get that $\widetilde{F}$ is completely continuous and u is a solution of (3.5), (3.6), (4.9) if and only if u is a fixed point of $\widetilde{F}$.

Denote by I the identity operator on $\mathbb{C}^1_D[0, T]$ and consider the parameter system of operator equations

$$(I - \lambda \widetilde{F})u = 0, \quad \lambda \in [0, 1]. \tag{4.12}$$

For $R \in (0, \infty)$, define $B(R) = \{u \in \mathbb{C}^1_D[0, T] : \|u\|_D < R\}$. By (4.2), (4.4), (4.5), (4.6), (4.7), (4.8), and (4.11), we can find $R_0 \in (0, \infty)$ such that $u \in B(R_0)$ for each $\lambda \in [0, 1]$

and each solution u of (4.12). So, for each $R \geq R_0$, the operator $\mathrm{I} - \lambda \widetilde{\mathrm{F}}$ is a homotopy on $\mathrm{cl}(\mathrm{B}(R)) \times [0,1]$ and its Leray-Schauder degree $\deg(\mathrm{I} - \lambda \widetilde{\mathrm{F}}, \mathrm{B}(R))$ has the same value for each $\lambda \in [0,1]$. Since $\deg(\mathrm{I}, \mathrm{B}(R)) = 1$, we conclude that

$$\deg\left(\mathrm{I} - \widetilde{\mathrm{F}}, \mathrm{B}(R)\right) = 1 \quad \text{for } R \in [R_0, \infty). \tag{4.13}$$

By (4.13), there is at least one fixed point of $\widetilde{\mathrm{F}}$ in $\mathrm{B}(R)$. Hence there exists a solution of the auxiliary problem (3.5), (3.6), (4.9).

Step 3. We find estimates for solutions of the auxiliary problem.

Let u be a solution of (3.5), (3.6), (4.9). We derive an estimate for $\|u\|_\infty$. By (4.7), (4.8), and (2.11), we obtain that $\widetilde{f}, \widetilde{\mathrm{J}}_i, \widetilde{\mathrm{M}}_i, i = 1, 2, \ldots, m$, satisfy (3.1), (3.2), and (3.3). Moreover, in view of (4.4), we have

$$\sigma_1(0) \leq \alpha(0, u(0) + u'(0) - u'(T)) \leq \sigma_2(0). \tag{4.14}$$

Thus u satisfies (3.8) by Lemma 3.1.

We find an estimate for $\|u'\|_\infty$. By the mean value theorem and (3.8), there are $\xi_i \in (t_i, t_{i+1})$ such that

$$\left| u'(\xi_i) \right| \leq \frac{\|\sigma_1\|_\infty + \|\sigma_2\|_\infty}{\Delta}, \quad i = 1, 2, \ldots, m. \tag{4.15}$$

Moreover, by (3.8) and (4.8), u satisfies (2.1) for a.e. $t \in [0,T]$. Therefore, integrating (2.1) and using (4.2), (4.3), and (4.15), we obtain

$$\|u'\|_\infty \leq \left| u'(\xi_i) \right| + \|m\|_1 < c. \tag{4.16}$$

Hence, by (4.7) and (4.9), we see that u fulfils (2.2) and $u(0) = u(T)$ (i.e., the first condition from (2.3) is satisfied).

Step 4. We verify that u fulfils the second condition in (2.3).

We must prove that $u'(0) = u'(T)$. By (4.9), this is equivalent to

$$\sigma_1(0) \leq u(0) + u'(0) - u'(T) \leq \sigma_2(0). \tag{4.17}$$

Suppose, on the contrary, that (4.17) is not satisfied. Let, for example,

$$u(0) + u'(0) - u'(T) > \sigma_2(0). \tag{4.18}$$

Then, by (4.4), we have $\alpha(0, u(0) + u'(0) - u'(T)) = \sigma_2(0)$. Together with (2.7) and (4.9), this yields

$$u(0) = u(T) = \sigma_2(0) = \sigma_2(T). \tag{4.19}$$

Inserting (4.19) into (4.18), we get

$$u'(0) > u'(T). \tag{4.20}$$

On the other hand, (4.19) together with (3.8) and (4.20) implies that

$$\sigma_2'(0) \geq u'(0) > u'(T) \geq \sigma_2'(T), \tag{4.21}$$

a contradiction to (2.7).

If we assume that $u(0) + u'(0) - u'(T) < \sigma_1(0)$, we can argue similarly and again derive a contradiction to (2.7).

So, we have proved that (4.17) is valid, which means that $u'(0) = u'(T)$. Consequently, u is a solution of (2.1), (2.2), and (2.3) satisfying (3.8). $\qquad\square$

Proof of Theorem 4.1. Put

$$c = r^* + ||\sigma_1'||_\infty + ||\sigma_2'||_\infty, \tag{4.22}$$

where $r^* \in (0, \infty)$ is given by Lemma 3.2 for $r = ||\sigma_1||_\infty + ||\sigma_2||_\infty$. For a.e. $t \in [0, T]$ and all $(x, y) \in \mathbb{R}^2$, define a function

$$g(t, x, y) = \begin{cases} f(t, x, y) & \text{if } |y| \leq c, \\ \left(2 - \dfrac{|y|}{c}\right) f(t, x, y) & \text{if } c < |y| < 2c, \\ 0 & \text{if } |y| \geq 2c. \end{cases} \tag{4.23}$$

Then σ_1 and σ_2 are, respectively, lower and upper functions of the auxiliary problem (2.2), (2.3), and

$$u'' = g(t, u, u'). \tag{4.24}$$

There exists a function $m^* \in \mathbb{L}[0, T]$ such that

$$|f(t, x, y)| \leq m^*(t) \tag{4.25}$$

for a.e. $t \in [0, T]$ and all $(x, y) \in [\sigma_1(t), \sigma_2(t)] \times [-2c, 2c]$. Hence

$$|g(t, x, y)| \leq m^*(t) \quad \text{for a.e. } t \in [0, T], \text{ all } (x, y) \in [\sigma_1(t), \sigma_2(t)] \times \mathbb{R}. \tag{4.26}$$

Since $g \in \mathrm{Car}([0, T] \times \mathbb{R}^2)$, we can apply Proposition 4.2 to problem (4.24), (2.2), (2.3) and get that this problem has a solution u fulfilling (3.8). Hence $||u||_\infty \leq r$. Moreover, by (4.1), u satisfies (3.27). Therefore, by Lemma 3.2, $||u'||_\infty \leq r^* \leq c$. This implies that u is a solution of (2.1), (2.2), and (2.3). $\qquad\square$

The next simple existence criterion, which follows from Theorem 4.1 and Remark 2.3, extends both [5, Theorem 4] and [13, Corollary 3.4].

COROLLARY 4.3. *Let (2.8) hold. Furthermore, assume that*

  (i) $M_i(0) = 0$ *and* $yM_i(y) \geq 0$ *for* $y \in \mathbb{R}$ *and* $i = 1, 2, \ldots, m$;
  (ii) *there are* $r_1, r_2 \in \mathbb{R}$ *such that* $r_1 < r_2$, $f(t, r_1, 0) \leq 0 \leq f(t, r_2, 0)$ *for a.e.* $t \in [0, T]$,
      $J_i(r_1) = r_1$, $J_i(x) \in [r_1, r_2]$ *if* $x \in [r_1, r_2]$, $J_i(r_2) = r_2$, $i = 1, 2, \ldots, m$;
  (iii) *there are h and ω satisfying (3.24) and (3.25) with* $\sigma_1(t) \equiv r_1$ *and* $\sigma_2(t) \equiv r_2$ *and
      such that (4.1) holds.*

Then the problem (2.1), (2.2), and (2.3) has a solution u fulfilling $r_1 \leq u \leq r_2$ on $[0, T]$.

Remark 4.4. Let $\sigma_1 < \sigma_2$ on $[0, T]$ and $\sigma_1(t_i+) < \sigma_2(t_i+)$ for $i = 1, 2, \ldots, m$. Having G and G_1 from the proof of Proposition 4.2, we define an operator $F : \mathbb{C}^1_D[0, T] \mapsto \mathbb{C}^1_D[0, T]$ by

$$
\begin{aligned}
(Fu)(t) = u(0) + u'(0) - u'(T) + \int_0^T G(t,s) f(s, u(s), u'(s)) ds \\
+ \sum_{i=1}^m G_1(t, t_i)(J_i(u(t_i)) - u(t_i)) + \sum_{i=1}^m G(t, t_i)(M_i(u'(t_i)) - u'(t_i)).
\end{aligned} \tag{4.27}
$$

Let r^* be given by Lemma 3.2 for $r = \|\sigma_1\|_\infty + \|\sigma_2\|_\infty$. Define a set

$$
\begin{aligned}
\Omega = \{ u \in \mathbb{C}^1_D[0, T] : \|u'\|_\infty < r^*, \; \sigma_1(t) < u(t) < \sigma_2(t) \text{ for } t \in [0, T], \\
\sigma_1(t_i+) < u(t_i+) < \sigma_2(t_i+) \text{ for } i = 1, 2, \ldots, m \}.
\end{aligned} \tag{4.28}
$$

As in [13, Lemma 3.1], we get that F is completely continuous and u is a solution of (2.1), (2.2), and (2.3) if and only if u is a fixed point of F. The proofs of Theorem 4.1 and Proposition 4.2 yield the following result about the Leray-Schauder degree of the operator $I - F$ with respect to Ω.

COROLLARY 4.5. *Let $\sigma_1 < \sigma_2$ on $[0, T]$ and $\sigma_1(t_i+) < \sigma_2(t_i+)$ for $i = 1, 2, \ldots, m$, and let the assumptions of Theorem 4.1 be satisfied. Further, assume that F and Ω are defined by (4.27) and (4.28), respectively. If $Fu \neq u$ for each $u \in \partial\Omega$, then*

$$
\deg(I - F, \Omega) = 1. \tag{4.29}
$$

Proof. Consider c and g from the proof of Theorem 4.1 and define $\widetilde{J}_i$, $\widetilde{M}_i$, $i = 1, 2, \ldots, m$, and $\widetilde{f}$ by (4.7) and (4.8), where we put g instead of f. Define $\widetilde{F}$ by (4.11) and put $\Omega_1 = \{ u \in \Omega : \sigma_1(0) < u(0) + u'(0) - u'(T) < \sigma_2(0) \}$. Suppose that $Fu \neq u$ for each $u \in \partial\Omega$. We have

$$
F = \widetilde{F} \quad \text{on cl}(\Omega_1). \tag{4.30}
$$

and

$$
(Fu = u, \; u \in \Omega) \Longrightarrow u \in \Omega_1. \tag{4.31}
$$

By the proof of Proposition 4.2, we have that each fixed point u of $\widetilde{F}$ satisfies (3.8) and consequently $\|u\|_\infty \leq r$. Hence, by (4.1), (4.8), and (4.23),

$$\left|u''(t)\right| = \left|g\left(t, u(t), u'(t)\right)\right| \leq \omega\left(\left|u'(t)\right|\right)\left(\left|u'(t)\right| + h(t)\right) \tag{4.32}$$

for a.e. $t \in [0, T]$ and for $|u'(t)| > 1$. Therefore Lemma 3.2 implies that $\|u'\|_\infty \leq r^*$. So, by (2.3), $u \in \mathrm{cl}(\Omega_1)$. Now, choose R in (4.13) such that $B(R) \supset \Omega$. Then, by the excision property of the degree, we get

$$\deg(I - F, \Omega) = \deg\left(I - F, \Omega_1\right) = \deg\left(I - \widetilde{F}, \Omega_1\right) = \deg\left(I - \widetilde{F}, B(R)\right) = 1, \tag{4.33}$$

wherefrom, taking into account (4.30), we obtain (4.29). $\qquad\square$

Remark 4.6. Following the ideas from [12, 13], the evaluation of $\deg(I - F, \Omega)$ enables us to prove the existence of solutions to problem (2.1), (2.2), and (2.3) also for nonordered lower/upper functions. This will be included in our next paper [11].

Acknowledgment

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