Existence of Infinitely Many Solutions for a Quasilinear Elliptic Problem on Time Scales

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Abstract

We study a boundary-value quasilinear elliptic problem on a generic time scale. Making use of the fixed-point index theory, sufficient conditions are given to obtain existence, multiplicity, and infinite solvability of positive solutions.

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1 Introduction

We are interested in the study of the following quasilinear elliptic problem:

\[
\begin{align*}
-(\phi_p(u^{\Delta}(t)))^\nabla &= f(u(t)) + h(t), \quad \forall t \in (0, T),
\quad T = T, \\
u^{\Delta}(0) &= 0,
\quad u(T) - u(\eta) = 0, \quad 0 < \eta < T,
\end{align*}
\]

(1)

where \( \phi_p(\cdot) \) is the \( p \)-Laplacian operator defined by \( \phi_p(s) = |s|^{p-2}s, \quad p > 1, \)

\((\phi_p)^{-1} = \phi_q\) with \( q \) the Holder conjugate of \( p \), i.e. \( \frac{1}{p} + \frac{1}{q} = 1, \) and \( T \) is a time-scale. We assume the following hypotheses:

(H1) The function \( f : (0, T) \to \mathbb{R}^+ \) is a continuous function;

(H2) The function \( h : T \to \mathbb{R}^+ \) is left dense continuous (i.e, \( h \in \mathcal{C}_{ld}(T, \mathbb{R}^+) \)).
Here \( \mathcal{C}_{ld}(T, \mathbb{R}^+) \) denotes the set of all left dense continuous functions from \( T \to \mathbb{R}^+ \); and \( h \in L^\infty(0, T) \).
Results on existence of radially infinity many solutions for (1) are proved using (i) variational methods [5, 10], where solutions are obtained as critical points of some energy functional on a Sobolev space, by imposing appropriate conditions on $f$; (ii) methods based on phase-plane analysis and the shooting method [11]; (iii) by adapting the technique of time maps [12]. For $p = 2$, $h = 0$, $T = \mathbb{R}$, problem (1) becomes a boundary-value problem of differential equations. Our results extend and include results of the earlier works to the case of a generic time-scale $T$, $p \neq 2$ and where $h$ is not identically zero. In the case of $h = 0$, $p = 2$, many existence results of dynamic equations on time scales are available, using different fixed point theorems [6, 17]. We remark that there are not many results concerning the $p$–Laplacian problems on time scales [18]. In this paper we prove existence of solutions by constructing an operator whose fixed points are solutions of (1). Our main ingredient is the following well-known fixed-point theorem of index theory.

Theorem 1 ([13, 14]). Suppose $E$ is a real Banach space, and $K \subset E$ is a cone in $X$. Let $\Omega_r = \{ u \in K, \|u\| < r \}$, and $F : \Omega_r \rightarrow K$ be a completely continuous operator satisfying $Fx \neq x$, for all $x \in \partial \Omega_r$. The following holds:

(i) if $\|Fx\| \leq \|x\|$, $\forall x \in \partial \Omega_r$, then $i(F, \Omega_r, K) = 1$;

(ii) if $\|Fx\| \geq \|x\|$, $\forall x \in \partial \Omega_r$, then $i(F, \Omega_r, K) = 0$,

where $i$ is the index of $F$.

The study of dynamic equations on time scales is a fairly new subject, and research in this area is rapidly growing. The theory of time scales has been created in order to unify continuous and discrete analysis, allowing a simultaneous treatment of differential and difference equations, and to extend those theories to so-called delta/nabla-dynamic equations. A vast literature has already emerged in this field: see e.g. [2, 4, 7]. For an introduction to time scales with applications, we refer the reader to [8, 9].

The outline of the paper is as follows. In Section 2 we give some preliminary results with respect to the calculus on time scales. Section 3 is devoted to the existence of positive solutions using fixed-point index theory. The remaining sections deal with multiplicity and infinite solvability solutions for (1).

2 Preliminary results on time scales

We begin by recalling some basic concepts of time scales. Then, we prove some preliminary results that will be needed in the sequel.

A time scale $\mathbb{T}$ is an arbitrary nonempty closed subset of the set $\mathbb{R}$ of real numbers. The operators $\sigma$ and $\rho$ from $\mathbb{T}$ to $\mathbb{T}$ are defined in [15, 16]:

$$
\sigma(t) = \inf\{ \tau \in \mathbb{T} : \tau > t \} \in \mathbb{T}, \quad \rho(t) = \sup\{ \tau \in \mathbb{T} : \tau < t \} \in \mathbb{T}.
$$
They are called the forward jump operator and the backward jump operator, respectively.

The point \( t \in \mathbb{T} \) is said to be left-dense, left-scattered, right-dense, or right-scattered, if \( \rho(t) = t, \rho(t) < t, \sigma(t) = t, \sigma(t) > t \), respectively. If \( \mathbb{T} \) has a right scattered minimum \( m \), we define \( \mathbb{T}_k = \mathbb{T} - \{m\} \); otherwise we set \( \mathbb{T}_k = \mathbb{T} \). Similarly, if \( \mathbb{T} \) has a left scattered maximum \( M \), we define \( \mathbb{T}_k = \mathbb{T} - \{M\} \); otherwise we set \( \mathbb{T}_k = \mathbb{T} \).

Let \( f : \mathbb{T} \to \mathbb{R} \) and \( t \in \mathbb{T}_k \) (assume \( t \) is not left-scattered if \( t = \sup \mathbb{T} \)). We define \( f^\Delta(t) \) to be the number (provided it exists) such that given any \( \epsilon > 0 \) there is a neighborhood \( U \) of \( t \) such that

\[
|f(\sigma(t)) - f(s) - f^\Delta(t)(\sigma(t) - s)| \leq |\sigma(t) - s|, \quad \text{for all } s \in U.
\]

We call \( f^\Delta(t) \) the delta derivative of \( f \) at \( t \). We remark that \( f^\Delta(t) \) is the usual derivative \( f' \) if \( \mathbb{T} = \mathbb{R} \) and the usual forward difference \( \Delta f \) (defined by \( \Delta f(t) = f(t+1) - f(t) \)) if \( \mathbb{T} = \mathbb{Z} \).

Similarly, for \( t \in \mathbb{T} \) (assume \( t \) is not right-scattered if \( t = \inf \mathbb{T} \)), the nabla derivative of \( f \) at the point \( t \) is defined in \([7]\) to be the number \( f^\nabla(t) \) (provided it exists) with the property that for each \( \epsilon > 0 \) there is a neighborhood \( U \) of \( t \) such that

\[
|f(\rho(t)) - f(s) - f^\nabla(t)(\rho(t) - s)| \leq |\rho(t) - s|, \quad \text{for all } s \in U.
\]

If \( \mathbb{T} = \mathbb{R} \), then \( f^\Delta(t) = f^\nabla(t) = f'(t) \). If \( \mathbb{T} = \mathbb{Z} \), then \( f^\nabla(t) = f(t) - f(t-1) \) is the backward difference operator.

We say that a function \( f \) is left-dense continuous \( (ld\text{-}continuous \ for \ short) \), provided \( f \) is continuous at each left-dense point in \( \mathbb{T} \) and its right-sided limit exists at each right-dense point in \( \mathbb{T} \). It is well-known that if \( f \) is \( ld \)-continuous and if \( F^\nabla(t) = f(t) \), then one can define the nabla integral by

\[
\int_a^b f(t)\nabla t = F(b) - F(a).
\]

If \( F^\Delta(t) = f(t) \), then we define the delta integral by

\[
\int_a^b f(t)\Delta t = F(b) - F(a).
\]

Function \( F \) is said to be an antiderivative of \( f \). For more details on time scales, the reader can consult \([1, 2, 3, 4, 8, 9]\) and references therein.

In the rest of the paper, \( \mathbb{T} \) is a closed subset of \( \mathbb{R} \) with \( 0 \in \mathbb{T}_k, T \in \mathbb{T}_k \). We denote \( E = C_{ld}([0,T],\mathbb{R}) \), which is a Banach space with the maximum norm

\[
\|u\| = \max_{[0,T]} |u(t)|.
\]
Lemma 2. Suppose that conditions \((H1)\) and \((H2)\) hold. Then, \(u(t)\) is a solution of the boundary-value problem if and only if \(u(t) \in E\) is a solution of the following equation:

\[
u(t) = \phi_q \left( \int_\eta^T (f(u(r) + h(r)) \nabla r) \right) + \int_0^t \phi_q \left( \int_s^T (f(u(r) + h(r)) \nabla r) \right) \Delta s.
\]

(2)

Proof. By integrating the equation (1) on \((s, T)\), we have

\[
\phi_p(u^{\triangle}(T)) = \phi_p(u^{\triangle}(s)) - \int_s^T (f(u(r) + h(r)) \nabla r).
\]

Then,

\[
\phi_p(u^{\triangle}(s)) = \phi_p(u^{\triangle}(T)) + \int_s^T (f(u(r) + h(r)) \nabla r).
\]

Using the boundary conditions, we have

\[
\phi_p(u^{\triangle}(s)) = \int_s^T (f(u(r) + h(r)) \nabla r).
\]

Thus,

\[
u^{\triangle}(s) = \phi_q \left( \int_s^T (f(u(r) + h(r)) \nabla r) \right).
\]

Integrating the last equation on \((0, t)\), we have

\[
u(t) = u(0) + \int_0^t \phi_q \left( \int_s^T (f(u(r) + h(r)) \nabla r) \right) \Delta s
\]

\[
= u^{\triangle}(\eta) + \int_0^t \phi_q \left( \int_s^T (f(u(r) + h(r)) \nabla r) \right) \Delta s
\]

\[
= \phi_q \left( \int_\eta^T (f(u(r) + h(r)) \nabla r) \right) + \int_0^t \phi_q \left( \int_s^T (f(u(r) + h(r)) \nabla r) \right) \Delta s.
\]

Inversely, if we suppose that (2) holds, it is easy to get the first equation of (1) by derivation, and to see that \(u\) satisfies the boundary value conditions in (1). Furthermore, \(u\) is obviously positive since \(\phi_q\) is non decreasing function and \(f\) and \(h\) are also positives functions. The proof of Lemma 2 is now complete.

On the other hand, we have \(-\phi_p(u^{\triangle}) \nabla = f(u(t)) + h(t)\). Then, since \(f, h \geq 0\), we have \((\phi_p(u^{\triangle})) \nabla \leq 0\) and \((\phi_p(u^{\triangle}(t_2)) \leq (\phi_p(u^{\triangle}(t_1)))\) for any \(t_1, t_2 \in [0, T]\) with \(t_1 \leq t_2\). It follows that \(u^{\triangle}(t_2) \leq u^{\triangle}(t_1)\) for \(t_1 \leq t_2\). Hence,
$u^\Delta(t)$ is a decreasing function on $[0, T]$. This means that the graph of $u(t)$ is concave on $[0, T]$.

Let $K \subset E$ be the cone defined by

$$K = \{ u \in E : u(t) \geq 0, u(t) \text{ is a concave function, } t \in [0, 1] \},$$

and $F : K \to E$ the operator

$$F u(t) = \phi_q \left( \int_0^T (f(u(s)) + h(s)) \nabla r \right) + \int_0^t \phi_q \left( \int_s^T (f(u(s)) + h(s)) \nabla r \right) \Delta s.$$

It is easy to see that $\mathbf{I}$ has a solution $u = u(t)$ if and only if $u$ is a fixed point of the operator $F$. One can also verify that $F(K) \subset K$ and $F : K \to K$ is completely continuous.

3 Existence of positive solutions

We define two open subsets $\Omega_1$ and $\Omega_2$ of $E$:

$$\Omega_1 = \{ u \in K : \| u \| < a \}, \quad \Omega_2 = \{ u \in K : \| u \| < b \}.$$

Without loss of generality, we suppose that $b < a$. For convenience, we introduce the following notation:

$$A = \frac{a - \alpha \| h \|_\infty^{1/p - 1}}{\alpha a}, \quad \text{where } \alpha = \phi_q(2^{p-2})\phi_q(T)(T+1),$$

$$B = \phi_p(T - \eta).$$

**Theorem 3.** Besides $(H1)$ and $(H2)$, suppose that $f$ also satisfies:

(i) $\max_{0 \leq u \leq a} f(u) \leq \phi_p(aA)$;

(ii) $\min_{0 \leq u \leq b} f(u) \geq \phi_p(bB)$.

Then, $\mathbf{I}$ has a positive solution.

**Proof.** If $u \in \partial \Omega_1$, we have:

$$\| F(u) \| \leq \phi_q \left( \int_0^T ((aA)^{p-1} + \| h \|_\infty) \nabla r \right) + \int_0^t \phi_q \left( \int_s^T ((aA)^{p-1} + \| h \|_\infty) \nabla r \right) \Delta s \leq \phi_q \left( ((aA)^{p-1} + \| h \|_\infty)(T - \eta) \right) + \int_0^T \phi_q \left( ((aA)^{p-1} + \| h \|_\infty)(T - s) \right) \Delta s$$
\[
\phi_q \left( (aA)^{p-1} + \|h\|_\infty \right) \phi_q(T) \\
+ \phi_q \left( (aA)^{p-1} + \|h\|_\infty \right) \int_0^T \phi_q(T-s) \triangle s \\
\leq \phi_q \left( (aA)^{p-1} \right) \phi_q(T) \\
+ \phi_q \left( (aA)^{p-1} + \|h\|_\infty^{1/p-1} \right) \phi_q(T)^T \\
\leq \phi_q \left( (aA)^{p-1} \right) \phi_q(T + 1).
\]

Using the elementary inequality
\[x^p + y^p \leq 2^{p-1}(x + y)^p,\]
and the form of \(A\), it follows that
\[
\|F(u)\| \leq \phi_q(T + 1)(2^{p-2}(aA + \|h\|_\infty^{1/p-1}) \\
\leq \|u\| = a.
\]

Therefore, \(\|F u\| \leq \|u\|\) for all \(u \in \partial \Omega_1\). Then, by Theorem 1
\[
i(F, \Omega_1, K) = 1. \tag{3}
\]

On the other hand, for \(u \in \partial \Omega_2\) we have:
\[
\|F(u)\| \geq \phi_q \left( \int_0^T f(u(r) \nabla r) - \int_0^T \int_s^T (f(u(r)) \nabla r) \triangle s. \\
\geq Bb\phi_q(T - \eta) \\
\geq b = \|u\| (\text{since } B = \phi_p(T - \eta)).
\]

Therefore, \(\|F u\| \geq \|u\|\) for all \(u \in \partial \Omega_2\). By Theorem 1
\[
i(F, \Omega_2, K) = 0. \tag{4}
\]

It follows by \(3\) and \(4\) that
\[
i(F, \Omega_1 \setminus \overline{\Omega_2}, K) = 1.
\]

Then \(T\) has a fixed point \(u \in \Omega_1 \setminus \overline{\Omega_2}\). Obviously, \(u\) is a positive solution of problem \(1\) and \(b < \|u\| < a\). The proof of Theorem 3 is complete. \(\square\)

### 4 Multiplicity

By multiplicity we mean the existence of an arbitrary number of solutions. We now obtain results on the multiplicity of positive solutions for \(1\) under the following assumptions: we suppose that there exist positive real numbers
\[0 < a_1 < a_2 < \ldots < a_{k+1},\]
such that
\textbf{Theorem 4.} Assume that (i)-(ii) hold. Then, problem (1) has at least \(k\) positive solutions \(u_1, \ldots, u_k\) such that
\[ a_i < \|u_i\| < a_{i+1}, \quad i = 1, \ldots, k. \]

\textit{Proof.} By continuity, there exist
\[ 0 < b_1 < a_1 < c_1 < b_2 < a_2 < c_2 < \ldots < b_{k+1} < a_{k+1} < +\infty \]
such that
\[ \min_{0 \leq u < b_{2i+1}} f(u) \geq \phi_p(b_{2i+1}B), \quad \min_{0 \leq u < c_{2i-1}} f(u) \geq \phi_p(c_{2i-1}B), \]
for \(i = 1, \ldots, \left\lfloor \frac{k+2}{2} \right\rfloor\), and
\[ \max_{0 \leq u < c_{2i}} f(u) \leq \phi_p(c_{2i}A), \quad \max_{0 \leq u < b_{2i}} f(u) \leq \phi_p(b_{2i}A), \]
for \(i = 1, \ldots, \left\lfloor \frac{k+1}{2} \right\rfloor\). Then, calling Theorem 3 to each interval \((c_i, b_{i+1}), i = 1, \ldots, k\), we obtain the intended result. \(\square\)

\section{Infinite solvability}

\textbf{Theorem 5.} If the following two conditions hold,
\begin{enumerate}
    \item[(i)] \(\liminf_{a \to 0} \frac{\max_{0 \leq u \leq a} \{f(u)\}}{p} \leq \phi_p(A)\),
    \item[(ii)] \(\limsup_{b \to 0} \frac{\max_{0 \leq u \leq b} \{f(u)\}}{p} \geq \phi_p(B)\),
\end{enumerate}
then, problem (1) has a sequence of positive solutions \((u_k)_{k \geq 1}\) such that \(\|u_k\| \to 0\) as \(k \to \infty\).

\textit{Proof.} From (i) and (ii), there exists a sequence of pairs of positive numbers \((a_k, b_k)_{k \geq 1}\) convergent to \((0, 0)\) such that
\[ \max_{0 \leq u \leq a_k} f(u) \leq \phi_p(a_k A), \]
\[ \min_{0 \leq u \leq b_k} f(u) \geq \phi_p(b_k B). \]

Suppose that
\[ a_1 > b_1 > a_2 > b_2 > \ldots > a_k > b_k > \ldots \]
Calling Theorem 3 on each pair \((a_k, b_k)_{k \geq 1}\), we conclude that (1) has a sequence of positive solutions \((u_k)_{k \geq 1}\) such that \(b_k \leq \|u_k\| \leq a_k\). \(\square\)
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