DECOMPOSITION CONDITIONS FOR TWO-POINT BOUNDARY VALUE PROBLEMS

WENYING FENG

(Received 1 December 1998)

ABSTRACT. We study the solvability of the equation \( x'' = f(t, x, x') \) subject to Dirichlet, Neumann, periodic, and antiperiodic boundary conditions. Under the assumption that \( f \) can be suitably decomposed, we prove approximation solvability results for the above equation by applying the abstract continuation type theorem of Petryshyn on \( A \)-proper mappings.

Keywords and phrases. Boundary value problem, Fredholm operator, \( A \)-proper mapping, feebly \( a \)-solvable.

2000 Mathematics Subject Classification. Primary 47H09; Secondary 34B15.

1. Introduction. Let \( f : [0, 1] \times \mathbb{R}^2 \to \mathbb{R} \) be a continuous function. The purpose of this paper is to establish some new existence results on the solvability of second order ODE's of the form

\[ x'' = f(t, x, x') \tag{1.1} \]

subject to one of the following boundary conditions:

\[ x(0) = x(1) = 0, \tag{1.2} \]
\[ x'(0) = x'(1) = 0, \tag{1.3} \]
\[ x(0) = x(1), \quad x'(0) = x'(1), \tag{1.4} \]
\[ x(0) = -x(1), \quad x'(0) = -x'(1). \tag{1.5} \]

The solvability of (1.1) subject to the above Dirichlet, Neumann, periodic, and antiperiodic boundary conditions has been extensively studied by many authors (see [1, 2, 3, 5, 6, 7, 9, 10]). In a recent paper [2], a decomposition condition for \( f \) is imposed to ensure the solvability of (1.1) with the boundary condition (1.2). The theorems of [2] were proved by using the transversality theorem.

In this paper, under the assumption that \( f \) can be suitably decomposed, we shall apply the abstract continuation type theorem of Petryshyn on \( A \)-proper mappings to prove approximation solvability results for (1.1) with the boundary conditions (1.2), (1.3), (1.4), and (1.5). Approximation solvability includes the classical Galerkin method. One of our theorems includes the result of [2]. When \( f \) is independent of \( x'' \), our results generalize the results of [9, 10] and show that certain restrictions imposed in [9, 10] are not needed in this case.
Some examples show that our theorems permit the treatment of equations to which the results of [2, 3, 7] do not apply.

2. Preliminaries. We recall the definition of the $A$-proper mapping which was introduced by Petryshyn (see [8]).

**Definition 2.1.** Let $X, Y$ be Banach spaces. Suppose that $\{X_n\} \subset X$ and $\{Y_n\} \subset Y$ are sequences of finite dimensional oriented spaces and $Q_n : Y \rightarrow Y_n$ is a linear projection for each $n \in \mathbb{R}^n$, then the scheme $\Gamma = \{X_n, Y_n, Q_n\}$ is said to be admissible for maps from $X$ to $Y$ provided that $\dim X_n = \dim Y_n$ for each $n$, dist$(x, X_n) = \inf \{\|x - v\|_X : v \in X_n\} \rightarrow 0$ as $n \rightarrow \infty$ for each $x \in X$, and $Q_n y \rightarrow y$ for each $y \in Y$. For a given map $T : D \subset X \rightarrow Y$ the equation

$$Tx = y \quad (2.1)$$

is said to be feebly approximation-solvable (a-solvable) relative to $\Gamma$ if there exists $N_y \in \mathbb{R}^n$ such that the finite dimensional equation

$$T_n(x) = Q_n y, \quad (x \in D_n = D \cap X_n, T_n = Q_n T|_{D_n}), \quad (2.2)$$

has a solution $x_n \in D_n$ for each $n \geq N_y$ such that $x_{n_j} \rightarrow x \in D$ in $X$ and $Tx = y$.

**Definition 2.2.** $T$ is said to be $A$-proper relative to $\Gamma$ if $T_n : D_n \subset X_n \rightarrow Y_n$ is continuous for each $n \in \mathbb{R}^n$ and if $\{x_{n_j} | x_{n_j} \in D_{n_j}\}$ is any bounded sequence in $X$ such that $T_{n_j}(x_{n_j}) \rightarrow g$ for some $g$ in $Y$, then there is a subsequence $\{x_{n_k}\}$ of $\{x_{n_j}\}$ and $x \in D$ such that $x_{n_k} \rightarrow x$ in $X$ and $Tx = g$.

For (2.1) to be $a$-solvable relative to a given $\Gamma$ the operator $T$ has essentially to be $A$-proper relative to $\Gamma$ (see [3]).

Let $L : X \rightarrow Y$ be a Fredholm operator of index zero. It was shown in [8] that if $Y$ has an admissible scheme then an admissible scheme $\Gamma_L$ (depending on $L$) can be constructed such that $L$ is $A$-proper relative to $\Gamma_L$. Suppose that $X = \ker(L) \oplus X_1, Y = Y_0 \oplus \im(L)$, where $\dim \ker(L) = \dim Y_0$. Let $Q$ be a projection of $Y$ onto $Y_0$ and assume that there exists a continuous bilinear form $\langle \cdot, \cdot \rangle$ on $Y \times X$ mapping $(y, x)$ into $[y, x]$ such that $y \in \im(L)$ if and only if $[y, x] = 0$ for every $x \in \ker(L)$.

Our results will be proved by applying the following abstract continuation type theorem for $A$-proper mappings.

**Theorem 2.3** (see [6, 7]). Let $L$ be a Fredholm operator of index zero and $N : X \rightarrow Y$ be a continuous nonlinear map. Suppose there exists a bounded open set $G \in X$ with $0 \in G$ such that

1. $L - \lambda N : G \rightarrow Y$ is $A$-proper relative to $\Gamma$ for each $\lambda \in [0, 1]$ with $N(G)$ bounded.
2. $Lx + \lambda Nx = \lambda y$ for $x \in \partial G$ and $\lambda \in (0, 1]$.
3. $QN x - Qy \neq 0$ for $x \in \partial G \cap \ker(L)$.
4. Either $[QN x - Qy, x] \geq 0$ or $[QN x - Qy, x] \leq 0$ for $x \in \partial G \cap \ker(L)$. Then the equation

$$Lx - Nx = y \quad (2.3)$$
is feebly $a$-solvable relative to $\Gamma$ and in particular it has a solution $x \in G$. If $x$ is the unique solution in $G$, then (2.3) is strongly $a$-solvable.

3. Existence results. We use $P_1, P_2, P_3, \text{and} P_4$ to denote (1.1) subject to the boundary condition (1.2), (1.3), (1.4), and (1.5), respectively. Our first three theorems deal with the simple case (3.1).

**Theorem 3.1.** Let $f : [0, 1] \times \mathbb{R}^2 \to \mathbb{R}$ be continuous. Consider the following boundary value problem:

$$x'' = f(t, x, x'), \quad x(0) = x(1) = 0. \quad (3.1)$$

Assume that $f$ has the decomposition

$$f(t, x, p) = g(t, x, p) + h(t, x, p) \quad (3.2)$$

such that

1. $\int_0^1 x g(t, x, x') \, dt \geq 0$ for all $x \in C^2[0, 1]$ with $x(0) = x(1) = 0$,
2. $|h(t, x, p)| \leq a|x| + b|p|,$

where $a > 0$, $b > 0$ and $a + b\pi < \pi^2$. Then (3.1) is feebly $a$-solvable in $C^2[0, 1]$.

**Proof.** Let $X = C^0_0 = \{x \in C^2[0, 1], x(0) = x(1) = 0\}$ endowed with the norm $\|x\| = \max \{\|x\|_{\infty}, \|x'\|_{\infty}, \|x''\|_{\infty}\}$, where $\|x\|_{\infty} = \max_{t \in [0, 1]} |x(t)|$. Let $\| \cdot \|_2$ be the usual norm of $L^2(0, 1)$ and let $L : X \to C[0, 1]$ be the linear operator defined by

$$Lx = x'', \quad \text{for} \ x \in X. \quad (3.3)$$

Define $N : C^1[0, 1] \to C[0, 1]$ to be the nonlinear mapping

$$N x(t) = f(t, x(t), x'(t)). \quad (3.4)$$

Let $J : C^2_0 \to C^1[0, 1]$ denote the compact natural embedding. Since $NJ$ is compact, $L - \lambda NJ : C^2_0 \to C^1[0, 1]$ is $A$-proper for each $\lambda \in [0, 1]$, [5]. Also, $L$ is invertible, so by Theorem 2.3, the $a$-solvability of (3.1) follows provided there exists an open bounded set $G \subset C^2_0$ such that

$$Lx - \lambda NJx \neq 0, \quad \text{for} \ (x, \lambda) \in (C^2_0 \cap \partial G) \times (0, 1]. \quad (3.5)$$

This is equivalent to proving the following subset of $C^2_0$ is bounded:

$$U = \{x \in C^2_0, \ Lx - \lambda NJx = 0, \ \lambda \in (0, 1]\}. \quad (3.6)$$

Let $x \in U$, then

$$x'' = \lambda(g(t, x, x') + h(t, x, x')). \quad (3.7)$$
Applying Wirtinger’s inequality [4]: \( \|x\|_2 \leq (1/\pi) \|x'\|_2 \), we obtain

\[
\|x'\|_2^2 = -\int_0^1 xx'' \, dt \\
= -\lambda \int_0^1 xg(t,x,x') \, dt - \lambda \int_0^1 xh(t,x,x') \, dt \\
\leq -\lambda \int_0^1 xh(t,x,x') \, dt \\
\leq a \int_0^1 |x|^2 \, dt + b \left( \int_0^1 |x|^2 \, dt \right)^{1/2} \left( \int_0^1 |x'|^2 \, dt \right)^{1/2} \\
\leq \frac{a + b\pi}{\pi^2} \|x'\|_2^2. \tag{3.8}
\]

By our assumption, \( a + b\pi < \pi^2 \), so \( x' = 0 \). Since \( x \in C^2_0 \), \( x(t) = 0 \). This completes the proof. \( \square \)

**Remark 3.2.** In the case \( g(t,x,x') = r(x)x' \), where \( r \) is continuous and \( r(x) \in C^1[0,1] \), condition (1) of Theorem 3.1 is always satisfied, since \( \int_0^1 xr(x)x' \, dt = 0 \) for all \( x \in C^2_0 \).

We use the following condition (see [2]) and Condition 3.4 for a continuous function \( g : [0,1] \times \mathbb{R}^2 \to \mathbb{R} \).

**Condition 3.3.** \( |g(t,x,p)| \leq A(t,x)\omega(p^2) \) for all \( (t,x,p) \in [0,1] \times \mathbb{R}^2 \), where \( A(t,x) \) is bounded on each compact subset of \([0,1] \times \mathbb{R}\), \( \omega \in C(\mathbb{R}^N, (0, +\infty)) \) is non-decreasing and satisfies

\[
\int_0^{+\infty} \frac{ds}{\omega(s)} = \infty. \tag{3.9}
\]

**Condition 3.4.** \( |g(t,x,p)| \leq \sum_{i=1}^n B_i(t,x)\omega_i(p) \) for all \( (t,x,p) \in [0,1] \times \mathbb{R}^2 \), where \( B_i(t,x) \) is bounded on compact subsets of \([0,1] \times \mathbb{R}\) and \( \omega_i(p) \) are functions such that

\[
\int_0^1 |x'(t)|^2 \, dt \leq M \Rightarrow \int_0^1 |\omega_i(x'(t))| \, dt \leq M_0, \tag{3.10}
\]

where \( M, M_0 \) are constants, \( M_0 \) may depend on \( M \).

The following theorem is a generalization of Theorem 1 in [2].

**Theorem 3.5.** Let \( f \) have the decomposition

\[
f(t,x,p) = g(t,x,p) + h(t,x,p). \tag{3.11}
\]

Assume that

1. \( \int_0^1 xg(t,x,x') \, dt \geq 0 \) for all \( x \in C^2_0 \);
2. \( |h(t,x,p)| \leq a|x| + b|p| + \sum_{i=1}^n c_i |x|^\alpha_i + \sum_{j=1}^m d_j |p|^\beta_j \), where \( a \geq 0, b \geq 0, 0 \leq \alpha_i, \beta_j < 1 \);
3. \( g(t,x,p) \) satisfies Condition 3.3 or Condition 3.4.

Then (3.1) is feebly \( a \)-solvable in \( C^2[0,1] \) provided that \( a + b\pi < \pi^2 \).
PROOF. By the same argument as in the proof of Theorem 3.1, we only need to prove that the set

\[ U = \{ x \in C^2_0, \, Lx - \lambda Nx = 0, \, \lambda \in (0,1) \} \]

(3.12)
is bounded. As in the proof of Theorem 3.1, for \( x \in U \),

\[
\|x'|\|_2^2 \leq \int_0^1 |x h(t,x,x')| \, dt
\]

\[
\leq \int_0^1 |x| \left( a|x| + b|x'| + \sum_{i=1}^n c_i |x|^{\alpha_i} + \sum_{j=1}^m d_j |x'|^{\beta_j} \right) \, dt
\]

\[
\leq a\|x\|_2^2 + b\|x\|_2^2 \|x'|\|_2 + \sum_{i=1}^n c_i \|x\|_2 \left( \int_0^1 |x|^{2\alpha_i} \right)^{1/2} + \sum_{j=1}^m d_j \|x\|_2 \left( \int_0^1 |x'|^{2\beta_j} \right)^{1/2}
\]

\[
\leq \left( \frac{a}{\pi^2} + \frac{b}{\pi^2} \right) \|x'|\|_2^2 + \sum_{i=1}^n c_i \|x\|_2 \|x'|\|_2^{1+\alpha_i} + \sum_{j=1}^m \frac{d_j}{\pi^2} \|x\|_2 \|x'|\|_2^{1+\beta_j}
\]

(3.13)

Suppose that \( \|x'|\|_2 \neq 0 \), since otherwise \( x = 0 \). By our assumption \( (a+b\pi)/\pi^2 < 1 \), we have

\[
\left( 1 - \frac{a+b\pi}{\pi^2} \right) \|x'|\|_2 \leq \frac{1}{\pi^2} \sum_{i=1}^n c_i \|x\|_2 \|x'|\|_2^{1+\alpha_i} + \frac{1}{\pi^2} \sum_{j=1}^m d_j \|x\|_2 \|x'|\|_2^{1+\beta_j}
\]

(3.14)

If \( \|x'|\|_2 \to \infty \), we will have a contradiction since \( 0 \leq \alpha_i, \, \beta_i < 1 \). So there exists a constant \( M > 0 \) such that \( \|x'|\|_2 \leq M \). This implies

\[
\|x\|_\infty \leq \int_0^1 |x'| \, dt \leq \|x'|\|_2 \leq M.
\]

(3.15)

Suppose that \( g \) satisfies Condition 3.3, then

\[
|x''| \leq A_1 \omega \left( x'^2 \right) + C + b \|x'| \| + \sum_{j=1}^m d_j \|x'|^{\beta_j}
\]

(3.16)

where \( A_1, \, C \) are positive constants. Since

\[
|x'|^{\beta_j} \leq \frac{1}{2} \left( 1 + |x'|^{2\beta_j} \right) \leq 1 + |x'|^2,
\]

(3.17)

we have

\[
|x''| \leq A_1 \omega \left( x'^2 \right) + C + d \left( 1 + |x'|^2 \right) \leq A \left( \omega \left( x'^2 \right) + 2 + |x'|^2 \right),
\]

(3.18)

where \( A = \max \{ A_1, C, d \} \). As in the proof of Theorem 1 in [2], equation (3.18) implies that \( |x'| \) is bounded (for completeness, we give the proof here). Each \( t \in [0,1] \) for which \( x'(t) \neq 0 \) belongs to some interval \([s_1,s_2] \subset [0,1] \) with \( x'(t) \neq 0 \) on \( (s_1,s_2) \).
and \( x'(s_1) = 0 \) or \( x'(s_2) = 0 \). Suppose that \( x'(s_1) = 0 \) and \( x'(t) > 0 \) on \( (s_1, s_2) \). Define \( z(t) = x'(t), \ t \in [s_1, s_2] \). Then (3.18) implies that

\[
\frac{2z(t)z'(t)}{\omega(z^2(t)) + z^2(t) + 2} \leq 2Ax'(t), \quad t \in [s_1, s_2].
\]  

(3.19)

By integrating this inequality, we obtain

\[
\int_{0}^{z^2(t)} ds \frac{d}{d s} \frac{d}{ds} \leq 4AM, \quad t \in (s_1, s_2).
\]  

(3.20)

The assumption \( \omega \in C(\mathbb{R}^N, (0, +\infty)) \) is nondecreasing and satisfies

\[
\int_{0}^{+\infty} ds \frac{d}{d s} \omega(s) = \infty,
\]  

(3.21)

implies that (see [1]),

\[
\int_{0}^{\infty} ds \frac{d}{d s} \omega(s) + s + 2 = \infty.
\]  

(3.22)

This ensures that there exists a constant \( M_1 > 0 \) such that \( |x'(t)| \leq M_1 \). Let

\[
M_2 = \sup_{t \in [0, 1], \ |x| \leq M_1 \ |p| \leq M_1} |f(t, x, p)|,
\]  

(3.23)

then \( \|x\| \leq \max\{M, M_1M_2\} \). Hence, \( U \) is bounded.

If \( g \) satisfies Condition 3.4, then there exists \( A_2 > 0 \) such that

\[
|x''| \leq A_2 \left( \sum_{i=1}^{r} |\omega_i(x')| + |x'|^2 + 1 \right).
\]  

(3.24)

Hence

\[
\int_{0}^{1} |x''| \ dt \leq A_2 \left( \sum_{i=1}^{r} \int_{0}^{1} |\omega(x')| \ dt + \int |x'|^2 \ dt + 1 \right) \leq A_2 (rM_0 + M + 1) = M_3.
\]  

(3.25)

Suppose that \( \xi \in [0, 1] \) is such that \( x'(\xi) = 0 \). Then \( x'(t) = \int_{\xi}^{t} x''(s) \ ds \), and hence

\[
||x'||_{\infty} \leq ||x''||_{1} \leq M_3.
\]  

(3.26)

This follows that \( U \) is bounded.

\[\Box\]

Remark 3.6. Theorem 1 in [2] is the special case of Theorem 3.5 when \( a = 0, b = 0, \) and \( n = m = 1 \).

Example 3.7. Consider the following boundary value problem:

\[
x'' = x^{2n+1} x'^2 + x' - (x)^{1/3}, \quad x(0) = x(1) = 0,
\]  

(3.27)
where $n$ is a natural number. Let
\[ g(t,x,p) = x^{2n+1}p^2, \quad h(t,x,p) = p - x^{1/3}. \] (3.28)

Then by Theorem 3.5, this boundary value problem is feebly $a$-solvable in $C^2[0,1]$ and in particular it has a solution in $C^2[0,1]$.

Obviously, Theorem 1 in [2] cannot be applied to it. Also, we cannot find constants $M > 0$ and $a,b \in \mathbb{R}$ such that
\[ x \geq M \implies f(t,x,0) > a \quad \text{while} \quad x \leq -M \implies f(t,x,0) < b \] (3.29)
since $f(t,x,0) \to -\infty$ as $x \to -\infty$ and $f(t,x,0) \to \infty$ as $x \to \infty$. Hence, Theorem 4.1 in [3] and Theorem 2.1 in [7] cannot be applied.

**Theorem 3.8.** Let $f, g, h$ be as in Theorem 3.5 and instead of conditions (1) and (3), $g$ satisfies the following condition:
\[ pg(t,x,p) \leq 0, \quad \text{for} \quad (t,x,p) \in [0,1] \times \mathbb{R}^2. \] (3.30)

Then (3.1) is feebly $a$-solvable in $C^2[0,1]$ provided that $a+b < 1/2$.

**Proof.** Again we will prove that $U$ is bounded. Let $x \in U$, there exists $\xi \in (0,1)$ such that $x'(\xi) = 0$. Hence
\begin{align*}
\frac{1}{2}(x'(t))^2 & = \int_{\xi}^{t} x'' \, ds \
& \leq \int_{\xi}^{t} x' h(s,x,x') \, ds \
& \leq \int_{0}^{1} |x'| |h(t,x,x')| \, dt \\
& \leq ||x'||_{\infty} \left( a \|x\|_{\infty} + b ||x'||_{\infty} + \sum_{i=1}^{n} c_i \|x\|_{\alpha_i} + \sum_{j=1}^{m} d_j ||x'||_{\beta_j} \right). \tag{3.31}
\end{align*}

Suppose that $||x'||_{\infty} \neq 0$, otherwise $x = 0$. Since $a+b < 1/2$ and
\[ ||x||_{\infty} \leq ||x'||_{1} \leq ||x'||_{\infty}, \] (3.32)
we obtain
\[ \left( \frac{1}{2} - a - b \right) ||x'||_{\infty} \leq \sum_{i=1}^{n} c_i \|x\|_{\alpha_i} + \sum_{j=1}^{m} d_j ||x'||_{\beta_j}. \] (3.33)

This implies that there exists $M > 0$ such that $||x'||_{\infty} \leq M$. By (3.32), $||x||_{\infty} \leq M$. Let
\[ M' = \sup_{t \in [0,1], \|x\|_{\infty} \leq M, |p| \leq M} |f(t,x,p)|, \] (3.34)
then $||x|| \leq \max\{M,M'\}$. Thus $U$ is bounded. \[ \square \]

Now, we consider $P2$, $P3$, and $P4$. These are resonance cases, since the linear part is noninvertible. In the following, let
\[ X_i = \{ x \in C^2[0,1] : x \text{ satisfies the boundary condition (1.i), } i = 2,3, \text{ or } 4 \}, \]
\[ U_i = \{ x \in X_i : x'' = \lambda f(t,x,x'), \lambda \in (0,1) \}, \] (3.35)
thus (1.1) subject to the boundary conditions (1.3), (1.4), and (1.5), respectively.
Theorem 3.9. Let $f : [0,1] \times \mathbb{R} \rightarrow \mathbb{R}$ be continuous. Assume that
\[
f(t,x,p) = g(t,x,p) + h(t,x,p),
\]
and $f$, $g$, and $h$ satisfy the following conditions:

1. There exists a constant $M_0 > 0$ such that $xf(t,x,0) > 0$ for $|x| > M_0$;
2. (a) $g$ satisfies Condition 3.3 or
   (b) $g$ satisfies Condition 3.4 and $\int_0^1 x g(t,x,x') \, dt \geq 0$ for all $x \in X_I$;
3. $|h(t,x,p)| \leq C(t,x) + D(t,x)|p|^2 + \sum_{j=1}^n d_j(t,x)|p|^\beta_j$, where $C(t,x), D(t,x), x \in C[0,1]$ and $d_j(t,x)$ are bounded on compact subsets of $[0,1] \times \mathbb{R}$ and $0 \leq \beta_j < 2$.

Let $M = \max_{t \in [0,1], \, |x| \leq M_0} |D(t,x)|$, then (Pi) is feebly a-solvable relative to $\Gamma$ provided that $M_0 M < 1$.

Proof. Let $L : X_I \rightarrow C[0,1]$ be the linear operator defined by $Lx = x''$. Then it is easily seen that $L$ is a Fredholm operator of index zero and $\ker(L) = \mathbb{R}$. Let $Nx = f(t,x,x')$ be the nonlinear map from $C^1[0,1]$ to $C[0,1]$ and $J_i : X_I \rightarrow C^1[0,1]$ be the compact continuous embedding. Then $L - \lambda N J_i$ is $A$-proper for each $\lambda \in [0,1]$. Moreover, let $Q \gamma = \int_0^1 \gamma'(t) \, dt$ be the projection and
\[
[y,x] = \int_0^1 y(t)x(t) \, dt
\]
be the bilinear form on $C[0,1] \times X_I$. For any $x \equiv c \in \ker(L)$, if $c > M_0$, then by assumption (1), $f(t,c,0) > 0$ and if $c < -M_0$, then $f(t,c,0) < 0$. Hence, $||x|| = |c| > M_0$ implies $QN J_i c \not= 0$. Assumption (1) also ensures that $[QN J_i c, c] \not= 0$ for any $c \in \ker(L)$ with $|c| > M_0$. So, by Theorem 2.3, to prove (Pi) is feebly a-solvable, we only need to prove $U_I$ is bounded.

Suppose that $x \in U_I$, Lemma 2.2 in [7] implies that $||x||_{\infty} \leq M_0$. Suppose $g$ satisfies 2(a), then by assumption (3), we obtain
\[
|x''(t)| \leq A(t,x)\omega \left((x'(t))^2\right) + C(t,x) + D(t,x)|x'(t)|^2 + \sum_{j=1}^n d_j(t,x)|x'(t)|^{\beta_j}
\leq A_1 \omega \left((x'(t))^2\right) + C_1 + M|x'(t)|^2 + \sum_{j=1}^n d_{j1} \left(|x'(t)|^2 + 1\right)
\leq A_2 \left(\omega(x'(t))^2 + 2 + |x'(t)|^2\right),
\]
where $A_1 = \max_{t \in [0,1], |x| \leq M_0} |A(t,x)|, C_1, d_{j1}$ are defined similarly and $A_2$ is a constant.

As above, there exists $M_1 > 0$, such that $||x''||_{\infty} \leq M_1$. This implies that $U_I$ is bounded.

Suppose that $g$ satisfies 2(b), then
\[
||x'||_{2}^2 = -\int_0^1 x x'' \, dt = -\lambda \int_0^1 x g(t,x,x') \, dt - \lambda \int_0^1 x h(t,x,x') \, dt
\leq \int |x||h(t,x,x')| \, dt \leq M_0 \int_0^1 \left(|C(t,x)| + D(t,x)|x'|^2 + \sum_{j=1}^n d_j(t,x)|x'|^{\beta_j}\right) \, dt
\leq M_0 C + M_0 M \int_0^1 |x'|^2 \, dt + \sum_{j=1}^n d_j \int_0^1 |x'|^{\beta_j} \, dt.
\]

(3.39)
Since $M_0M < 1$, and by Holder’s inequality,

$$
\int_0^1 |x'|^{\beta_j} dt \leq \left( \int_0^1 |x'|^2 dt \right)^{\beta_j/2} = \|x'|^2_{L^2},
$$

so

$$(1 - M_0M)\|x'|^2_{L^2} \leq M_0C' + \sum_{j=1}^n d_j' \|x'|^{\beta_j}_{L^2}.\tag{3.41}$$

This implies that there exists $M_2 > 0$ such that $\|x'|^2_{L^2} \leq M_2$ for $0 \leq \beta_j < 2$. Since $g$ satisfies Condition 3.4, we obtain

$$
\int_0^1 |x''(t)| dt \leq A \int_0^1 |\omega(x')| dt + C' + M \int_0^1 |x'|^2 dt + \sum_{j=1}^n d_j' \int_0^1 (|x'(t)|^2 + 1) \leq M_3.\tag{3.42}
$$

$x \in X_i$ implies that there exists $\xi \in [0,1]$ such that $x'(\xi) = 0$, hence

$$
\|x'|^\infty = \left\| \int_\xi^t x''(s) ds \right\|^\infty \leq \|x''\|^1 \leq M_3.\tag{3.43}
$$

Thus, we have proved that $U_i$ is bounded, which completes the proof. \qed

**Remark 3.10.** In assumption (3) of Theorem 3.9, since $|p|^\beta \leq 1 + |p|^2$, the third term is included in the first two terms, but it is convenient to make this split since the bound on the $|p|^2$ term only is important.

**Remark 3.11.** In [10], the authors obtained the results on the existence of a solution to the following boundary value problem:

$$
(p(t)x')' + \tilde{f}(t,x,x',x'') = y(t), \quad x'(0) = x'(T) = 0,\tag{3.44}
$$

and in [9] they studied the boundary value problem,

$$
x'' + g_1(x)x' + \tilde{f}(t,x,x',x'') = y(t), \quad x(0) = x(1), \quad x'(0) = x'(1).\tag{3.45}
$$

In (3.44), $p \in C^1[0,T]$ and $p_0 = \min\{p(t) \mid 0 \leq t \leq T\} > 0$. When $\tilde{f}$ is independent of $x''$, let

$$
\tilde{h}(t,x,x') = \tilde{f}(t,x,x') - y(t),\tag{3.46}
$$

equation (3.44) can be rewritten in the following form (let $T = 1$):

$$
x'' = \frac{p'(t)}{p(t)}x' - \frac{\tilde{h}(t,x,x')}{p(t)}, \quad x'(0) = x'(1) = 0.\tag{3.47}
$$

To apply Theorem 3.9 to the boundary value problem (3.47), let

$$
g(t,x,p) = -\frac{p'(t)}{p(t)}p, \quad h(t,x,p) = -\frac{\tilde{h}(t,x,p)}{p(t)}.\tag{3.48}
$$
Then \( g \) satisfies Condition 3.3 with \( \omega(p) = p^{1/2} \). Assume that \(|\hat{f}(t,x,p)| \leq A + B|x| + C|p|\), since the condition (H4(ii)) or (H4(iii)) of [10] implies assumption (1) of Theorem 3.9, we obtain boundary value problem (3.47) is feebly \( a \)-solvable provided (H4(iii)) of (H4(ii)) of [10] holds. Thus when \( f \) does not depend on \( x'' \), in Theorem 2.1 in [10], the conditions \( BT^2 + \pi T(C + p_1) \leq \pi^2 p_0 \) of (H1) and (H2), (H3) are not necessary.

Similarly, when \( f \) is independent of \( x'' \), equation (3.45) can be rewritten as

\[ x'' = -g_1(x)x' - \hat{h}(t,x,x'), \quad x(0) = x(1), \quad x'(0) = x'(1). \]  

(3.49)

Let

\[ g(t,x,p) = -g_1(x)p, \quad h(t,x,p) = -\hat{h}(t,x,p). \]  

(3.50)

Then \( g \) satisfies Condition 3.4 since \( \int_0^1 xg_1(x)x' \, dt = 0 \) for any \( x \in X_3 \). Assume that \(|\hat{f}(t,x,p)| \leq A + B|x| + C|p|\), then condition (H4) of [9] ensures assumption (1) of Theorem 3.9. Applying Theorem 3.9, we obtain that boundary value problem (3.49) is feebly \( a \)-solvable provided (H4) of [9] holds. Hence in this case, in Theorem 2.1 in [9], the conditions \( B + \pi C < 2\pi^2 \) of (H1) and (H2), (H3) are not needed.

**Theorem 3.12.** Let \( f(t,x,p) = g(t,x,p) + h(t,x,p) \). Assume that

1. there exists \( M_0 > 0 \) such that \( x\hat{f}(t,x,0) > 0 \) for \( |x| > M_0 \);
2. \( pg(t,x,p) \geq 0 \) or \( pg(t,x,p) \leq 0 \) for \( (t,x,p) \in [0,1] \times \mathbb{R}^2 \);
3. \( |h(t,x,p)| \leq C(t,x) + D(t,x)|x'| + \sum_{j=1}^n d_j(t,x)|x'|^{\alpha_j}, \) where \( C(t,x), D(t,x), \) and \( d_j(t,x) \) are bounded on compact subsets of \([0,1] \times \mathbb{R} \) and \( 0 \leq \alpha_j < 1 \).

Let \( M = \max_{t \in [0,1], |x| \leq M_0} |D(t,x)| \), then (Pi) is feebly \( a \)-solvable relative to \( \Gamma \) provided that \( M < 1/2 \) if \( pg(t,x,p) \leq 0 \) and \( M < 1/4 \) if \( pg(t,x,p) > 0 \).

**Proof.** By the same argument with that in the proof of Theorem 3.9, we only need to prove \( U_i \) is bounded. Let \( x \in U_i \), then \( \|x\|_\infty \leq M_0 \) by Lemma 2.3 in [7]. Let \( \xi \in [0,1] \) be such that \( x'(\xi) = 0 \), and assume that \( pg(t,x,p) > 0 \) and \( M < 1/4 \). Then

\[
\frac{1}{2} (x'(t))^2 = \lambda \int_{\xi}^t x'g(s,x,x') \, ds + \lambda \int_{\xi}^t x'h(s,x,x') \, ds
\leq \int_{0}^1 x'g(s,x,x') \, ds + \int_{0}^1 |x'h(s,x,x')| \, ds.
\]  

(3.51)

Since \( x \in X_i \), so

\[
\int_{0}^1 x'' \, dt = \lambda \int_{0}^1 (x'g(t,x,x') + x'h(t,x,x')) \, dt = 0.
\]  

(3.52)

Hence,

\[
\frac{1}{2} (x'(t))^2 \leq 2 \int_{0}^1 |x'h(s,x,x')| \, dt.
\]  

(3.53)

Thus

\[
\frac{1}{4} (x'(t))^2 \leq \|x''\|_\infty \int_{0}^1 \left( C(t,x) + D(t,x)|x'| + \sum_{j=1}^n d_j(t,x)|x'|^{\alpha_j} \right) \, dt
\leq \|x''\|_\infty \left( C + M\|x''\|_\infty + \sum_{j=1}^n d_j\|x''\|_\infty^{\alpha_j} \right).
\]  

(3.54)
Assume that \(|x'|_\infty \neq 0\), then

\[
\left(\frac{1}{4} - M\right)||x'||_\infty \leq C' + \sum_{j=1}^{n} d_j^j ||x'||_\infty^\alpha_j. \tag{3.55}
\]

Since \(\alpha_j < 1\), we obtain that there exists \(M_1 > 0\) such that \(||x'||_\infty \leq M_1\). In the case \(pg(t,x,p) \leq 0\) and \(M < 1/2\), instead of (3.51), we have

\[
\frac{1}{2} (x'(t))^2 = \lambda \int_{\xi}^{t} x'g(s,x,x') \, ds + \lambda \int_{\xi}^{t} x'h(s,x,x') \, ds
\leq \int_{0}^{1} |x'h(s,x,x')| \, ds. \tag{3.56}
\]

So, by the same proof with above, there exists \(M_2 > 0\) such that \(||x'|_\infty \leq M_2\). Thus in both cases, \(U_i\) is bounded.

**Example 3.13.** We study the following equation:

\[x'' = \pm x^{2n+1} + Q(t,x) + |x'|^{1/2}\]  \tag{3.57}

subject to the boundary conditions (1.3), (1.4), and (1.5), where \(n\) is a natural number and \(Q(t,x)\) is a continuous function. Assume that there exists \(M_0 > 0, xQ(t,x) > 0\) for \(|x| > M_0\). By Theorem 3.12, the above boundary value problems is feebly \(a\)-solvable since \(D(t,x) = 0\). Since we cannot find \(A(t,x)\) such that

\[|\pm p^{2n+1} + Q(t,x) + |p|^{1/2}| \leq A(t,x)p^2 + C(t,x), \tag{3.58}\]

Theorem 2.1 in [7] and Theorem 4.1 in [3] cannot be used.

In our last theorem, we impose a condition which is similar to the condition (H3) of [10].

**Theorem 3.14.** Let \(f(t,x,p) = g(t,x,p) + h(t,x,p)\). Assume that

1. there exists \(M_1 > 0\) such that either \(cf(t,c,0) \geq 0\) for all \(|c| \geq M_1\) or \(cf(t,c,0) \leq 0\) for all \(|c| \geq M_1\);
2. there exists \(M_2 > 0\) such that \(\int_{0}^{1} f(t,x,x') \, dt \neq 0\) for \(x \in X_i\) with \(|x(t)| > M_2\) for \(t \in \mathbb{R}^2\);
3. \(pg(t,x,p) \geq 0\) or \(pg(t,x,p) \leq 0\) for \((t,x,p) \in [0,1] \times \mathbb{R}^2\);
4. \(|h(t,x,p)| \leq a|x| + b|p| + c|x|^{\alpha} + d|p|^{\beta} + e, \) where \(0 \leq \alpha, \beta < 1, \) and \(a,b,c,d,e\) are constants.

Then (Pi) is feebly \(a\)-solvable relative to \(\Gamma\) provided that \(a + b < 1/2\) if \(pg(t,x,p) \leq 0\) and \(a + b < 1/4\) if \(pg(t,x,p) > 0\).

**Proof.** Let \(L,N,J_i,Q\) and the bilinear form \([y,x]\) be as in the proof of Theorem 3.9. For \(c \in \text{ker}(L)\), by assumption (2), \(QNc \neq 0\) if \(|c| \geq M_2\). Moreover, according to assumption (1), \([QNc,c] \geq 0\) for all \(|c| \geq M_1\). Hence, by Theorem 2.3, (Pi) is feebly \(a\)-solvable if \(U_i\) is bounded.

Let \(x \in U_i\) and \(\xi \in [0,1]\) be such that \(x' (\xi) = 0\). By assumptions (3) and (4), using the same calculation with that in (3.51) and (3.56), we obtain that if \(pg(t,x,p) > 0\),
then

\[
\frac{1}{4} \|x'\|_2^2 \leq \|x'\|_\infty \left( a \|x\|_\infty + b \|x'\|_\infty + c \|x\|_\alpha + d \|x'\|_\beta + e \right)
\]  

(3.59)

and if \( pg(t, x, p) \leq 0 \),

\[
\frac{1}{2} \|x'\|_2^2 \leq \|x'\|_\infty \left( a \|x\|_\infty + b \|x'\|_\infty + c \|x\|_\alpha + d \|x'\|_\beta + e \right) \].
\]  

(3.60)

Assume that \( \|x'\|_\infty \neq 0 \). Since \( x \in X_i \), \( Nx \in \text{im}(L) \), so \( QNx = 0 \). Assumption (2)

ensures that there exists \( \zeta \in [0, 1] \) such that \( |x(\zeta)| \leq M_2 \). Writing \( x(t) = \int_\zeta^t x'(s) \, ds + x(\zeta) \) gives

\[
\|x\|_\infty \leq \|x'\|_1 + M_2 \leq \|x'\|_\infty + M_2.
\]  

(3.61)

From the above discussion, in the case \( pg(t, x, p) > 0 \), we obtain

\[
\left( \frac{1}{4} - a - b \right) \|x'\|_\infty \leq M + c (\|x'\|_\infty + M_2)^\alpha + d \|x'\|_\beta + e.
\]  

(3.62)

In the case \( pg(t, x, p) \leq 0 \), a similar inequality is obtained. These imply that there exists \( M_3 > 0 \) such that in both cases, \( \|x'\|_\infty \leq M_3 \). By (3.61), \( \|x\|_\infty \leq M_3 \). Thus, we have proved that \( U_i \) is bounded.

REMARK 3.15. It is easy to see that in condition (4) of Theorem 3.14, \( c |x|^\alpha \)

and \( d |p|^\beta \) can, respectively, be replaced by \( \sum_{i=1}^n c_i |x|^\alpha_i \) and \( \sum_{j=1}^m d_j |p|^\beta_j \), where \( 0 \leq \alpha_i, \beta_j \leq 1 \).

ACKNOWLEDGEMENT. I would like to express my thanks to Professor J. R. L. Webb for valuable discussions.

REFERENCES


WENYING FENG: COMPUTER SCIENCE STUDIES PROGRAM, TRENT UNIVERSITY, PETERBOROUGH, ONTARIO, CANADA K9J 7B8
E-mail address: wfeng@trentu.ca
Mathematical Problems in Engineering

Special Issue on
Time-Dependent Billiards

Call for Papers

This subject has been extensively studied in the past years for one-, two-, and three-dimensional space. Additionally, such dynamical systems can exhibit a very important and still unexplained phenomenon, called as the Fermi acceleration phenomenon. Basically, the phenomenon of Fermi acceleration (FA) is a process in which a classical particle can acquire unbounded energy from collisions with a heavy moving wall. This phenomenon was originally proposed by Enrico Fermi in 1949 as a possible explanation of the origin of the large energies of the cosmic particles. His original model was then modified and considered under different approaches and using many versions. Moreover, applications of FA have been of a large broad interest in many different fields of science including plasma physics, astrophysics, atomic physics, optics, and time-dependent billiard problems and they are useful for controlling chaos in Engineering and dynamical systems exhibiting chaos (both conservative and dissipative chaos).

We intend to publish in this special issue papers reporting research on time-dependent billiards. The topic includes both conservative and dissipative dynamics. Papers discussing dynamical properties, statistical and mathematical results, stability investigation of the phase space structure, the phenomenon of Fermi acceleration, conditions for having suppression of Fermi acceleration, and computational and numerical methods for exploring these structures and applications are welcome.

To be acceptable for publication in the special issue of Mathematical Problems in Engineering, papers must make significant, original, and correct contributions to one or more of the topics above mentioned. Mathematical papers regarding the topics above are also welcome.

Authors should follow the Mathematical Problems in Engineering manuscript format described at http://www.hindawi.com/journals/mpe/. Prospective authors should submit an electronic copy of their complete manuscript through the journal Manuscript Tracking System at http://mts.hindawi.com/ according to the following timetable:

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript Due</td>
<td>March 1, 2009</td>
</tr>
<tr>
<td>First Round of Reviews</td>
<td>June 1, 2009</td>
</tr>
<tr>
<td>Publication Date</td>
<td>September 1, 2009</td>
</tr>
</tbody>
</table>

Guest Editors

Edson Denis Leonel, Department of Statistics, Applied Mathematics and Computing, Institute of Geosciences and Exact Sciences, State University of São Paulo at Rio Claro, Avenida 24A, 1515 Bela Vista, 13506-700 Rio Claro, SP, Brazil; edleonel@rc.unesp.br

Alexander Loskutov, Physics Faculty, Moscow State University, Vorob’evy Gory, Moscow 119992, Russia; loskutov@chaos.phys.msu.ru

Hindawi Publishing Corporation
http://www.hindawi.com