GHIZZETTI’S THEOREM FOR PIECEWISE CONTINUOUS SOLUTIONS

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ABSTRACT. We obtain that certain second order differential equations have discontinuous solutions which behave asymptotically as straight lines.

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1. INTRODUCTION.
Many applied problems in physics, biology, economics, etc., are submitted to noncontinuous perturbations. Biological systems such as heart beats, blood flows, pulse frequency modulated systems and models for biological neural nets exhibit an impulsive behavior. This justify the increasing interest on the differential equations with impulse action.

We wish to study the second order impulsive differential equation

\[ y''(t) = f(t, y(t), y'(t)), \quad t \neq t_i, \quad t \geq a > 0 \quad (P1) \]

\[ \Delta y(t) = g_1(t, y(t), y'(t)), \quad t = t_i \quad (P2) \]

\[ \Delta y'(t) = g_2(t, y(t), y'(t)), \quad t = t_i \quad (P3) \]

\[ y(t_0) = y_0, \quad a \leq t_0 < t_1 \quad (P4) \]

We assume the following basic hypotheses

(F) \( f: I \times C^2 \to C \) a continuous function such that

\[ |f(t, y_1, y_2)| \leq \lambda_1(t)|y_1| + \lambda_2(t)|y_2|. \quad (1.1) \]

(G) \( g_i: \nu \times C \to C \) are two continuous functions such that

\[ |g_i(t, y_1, y_2)| \leq \gamma_i(t)(|y_1| + |y_2|) = 1.2. \quad (1.2) \]

(I) \( \lambda(s) = s\lambda_1(s) + \lambda_2(s) \in L_1(I), \gamma(t_k) = t_k\gamma_2(t_k) + \gamma_1(t_k) \in \ell_1. \)

We will demonstrate that for every \( t_0 \geq a > 0 \), any solution \( y \) of problem (P) is defined on all of \( [t_0, \infty) \) and as \( t \to \infty \), it satisfies

\[ y(t) = \delta_1 + \theta(\Lambda(t)) + (\delta_2 + \theta(\Lambda(t)))t \quad (1.3) \]

and
where $\delta_i (i = 1, 2)$ are constants and

$$A(t) = \int_t^\infty \lambda(s)ds + \sum_{t_k \in (t, \infty)} \gamma(t_k).$$

Furthermore, under the stronger condition

$$(I') \quad s^2 \lambda_1(s) + s \lambda_2(s) \in L_1(I); \quad t_k^2 \gamma_2(t_k), t_k \gamma_1(t_k) \in L_1,$$

the relation

$$y(t) = \delta_1 + \delta_2 t + O(A(t)), t \to \infty$$

holds, where

$$A_1(t) = \int_t^\infty s \lambda(s)ds + \sum_{t_k \in (t, \infty)} t_k \gamma(t_k).$$

In this way, we extend the classical Ghizzetti's Theorem [2] for ordinary differential equations (see [5] to [9]) to problem (P).

Let $I_v = I - \nu$ and $C_v^+ (I) = \{ u \in C(I_v) \mid u(t^-) = u(t_i^-) \text{ and } u(t_i^+) \text{ exist } i = 1, 2, \ldots \}$. As usual, $u(t_i^-)$ and $u(t_i^+)$ denote the left and right limit of $u(t)$ as $t \to t_i$.

Next, we establish without proof (see [1], [3]) a Gronwall's inequality.

**Lemma 1.** Let $0 < \nu, \lambda \in C_v^+ ([t_0, \infty)), \gamma : \nu \to (0, \infty)$ and $c \geq 0$. The inequality

$$u(t) \leq c + \int_{t_0}^t \lambda(s)u(s)ds + \sum_{(t_0, t)} \gamma(t_k)u(t_k), t \geq t_0$$

implies

$$u(t) \leq c \exp \left[ \int_{t_0}^t \lambda(s)ds + \sum_{(t_0, t)} \gamma(t_k) \right],$$

where

$$\sum_{(t_0, t)} \gamma(t_k) = \sum_{t_k \in (t_0, t)} \gamma(t_k).$$

2. **MAIN RESULTS.**

We will prove the following results:

**Theorem 1.** Under conditions (F), (G), and (I), for every $t_0 \geq a > 0$ any solution $y$ of problem (P) is defined on all of $[t_0, \infty)$ and it satisfies formulae (1.3) and (1.4).

**Theorem 2.** Under conditions (F), (G), and (I), there exist nonoscillatory solutions $y$ of problem (P).

**Theorem 3.** Under conditions (F), (G), and (I'), the conclusion of Theorem 1 is true and formula (1.6) holds. Moreover, there exists solutions $y$ of problem (P) satisfying (1.6) with $\delta_i \neq 0$ $(i = 1, 2)$.

**Proof of Theorem 1.** Let

$$y = A(t) + B(t)t$$

under the condition

$$A'(t) + B'(t)t = 0 \text{ for } t \neq t_i.$$  

Then

$$y'(t) = B(t)$$

and hence

$$B'(t) = \tilde{f}(t), \text{ for } t \neq t_i,$$

where $\tilde{f}(t) = \tilde{f}(t, y(t), y'(t))$. Solving equations (2.1)-(2.4) we get for $t \neq t_i$,

$$A(t) = A(t_0) - \int_{t_0}^t s\tilde{f}(s)ds$$

$$B(t) = B(t_0) + \int_{t_0}^t \tilde{f}(s)ds.$$
For the impulse effect, from

\[ \Delta y = \Delta A = \Delta(Bt) = \Delta A + t \Delta B \]

we get

\[ \Delta A + t \Delta B = \tilde{y}_1 \]

\[ \Delta B = \tilde{y}_2, \]

where

\[ \tilde{y}_1(t) = g_1(t, y(t), y'(t)). \]

So

\[
\begin{cases}
\Delta A = \tilde{y}_1(t) - \tilde{y}_2(t), & t = t_i \\
\Delta B = \tilde{y}_2(t) & t = t_i
\end{cases}
\]  

(2.6)

Next, we consider the impulse integral system (2.5)-(2.6). It is equivalent to the system

\[ \begin{align*}
A(t) &= A(t_0) - \int_{t_0}^{t} \tilde{f}(s) \, ds + \sum_{t_k \in (t_0, t)} \left[ g_1(t_k, y(t_k), y'(t_k)) - \int_{t}^{t_k} g_2(t_k, y(t_k), y'(t_k)) \right]
\end{align*} \]  

(2.7)

\[ \begin{align*}
B(t) &= B(t_0) + \int_{t_0}^{t} \tilde{f}(s) \, ds + \sum_{t_k \in (t_0, t)} g_2(t_k, y(t_k), y'(t_k))
\end{align*} \]  

(2.8)

From (2.1), (2.3) and the hypotheses with \( v(s) = s^{-1} |A(s)| + |B(s)| \) we get

\[ |f(s, y(s), y'(s))| \leq \lambda_1(s) |y(s)| + \lambda_2(s) |y'(s)| \]

\[ \leq s \lambda_1(s) |s^{-1} A(s)| + \lambda_2(s) |B(s)| \leq (s \lambda_1(s) + \lambda_2(s)) v(s) \]

and

\[ |g_1(t_k, y(t_k), y'(t_k))| \leq \gamma_1(t_k) \left[ |A(t_k)| + t_k B(t_k) | + |B(t_k)| \right] \leq t_k \gamma_1(t_k) v(t_k), \]

\[ |g_2(t_k, y(t_k), y'(t_k))| \leq t_k \gamma_2(t_k) v(t_k). \]  

(2.9)

Now, from (2.7) and (2.9) we obtain for \( t \geq t_0 \)

\[ \frac{|A(t)|}{t} \leq \frac{|A(t_0)|}{t} + \int_{t_0}^{t} \frac{\tilde{f}(s)}{t} \, ds + \sum_{t_k < t} \left[ \tilde{y}_1(t_k) - t_k \tilde{y}_2(t_k) \right] \]

\[ \leq t_0^{-1} |A(t_0)| + \int_{t_0}^{t} \frac{\lambda(s)}{t} v(s) \, ds + \sum_{t_k < t} \left[ \gamma_1(t_k) + t_k \gamma_2(t_k) \right] v(t_k) \]  

(2.10)

Similarly, from (2.8) and (2.9) we get

\[ |B(t)| \leq |B(t_0)| + \int_{t_0}^{t} (s \lambda_1(s) + \lambda_2(s)) v(s) \, ds + \sum_{t_k < t} t_k \gamma_2(t_k) v(t_k). \]  

(2.11)

Adding (2.10) to (2.11) we get

\[ v(t) \leq v(t_0) + \int_{t_0}^{t} 2 \lambda(s) v(s) \, ds + \sum_{t_0}^{t} 2 \gamma(t_k) v(t_k) \]

where \( \lambda(s) = s \lambda_1(s) + \lambda_2(s), \gamma(s) = s \gamma_2(s) + \gamma_1(s). \) From Lemma 1, we obtain

\[ v(t) \leq v(t_0) \prod_{t_0}^{t} (1 + 2 \gamma(t_k)) \cdot \exp(2 \int_{t_0}^{t} \lambda(s) \, ds) (t \geq t_0). \]

Since \( \lambda \in L_1, \gamma \in L_1(\nu) \) we get that \( v \) is bounded and hence both \( t^{-1} A(t), B(t) \) are also bounded. From (2.9) we get that \( f(s, y(s), y'(s)) \in L_1([a, \infty)) \) and \( g_1(t_k, y(t_k), y'(t_k)), g_2(t_k, y(t_k), y'(t_k)) \in \ell_1. \) Then, from (2.8), \( B \) converges, i.e.,

\[ B(t) = \delta_2 + o(1) \text{ as } t \to \infty \]

and by (2.8)

\[ B(t) = \delta_2 + 0(A(t)) \]

where

\[ A(t) = \int_{t}^{\infty} \lambda(s) \, ds + \sum_{t, \infty} \gamma(t_k). \]

On the other hand, the functions of \( t \)
are increasing and bounded since $\hat{f} \in L_1; \hat{g}_i(t_k) \in \ell_1 (i = 1, 2)$. Then they converge as $t \to \infty$.

Therefore the functions

$$\int_{t_0}^{t} \frac{(t-s)}{t} \hat{f}(s) ds + \sum_{(t_0,t)} \frac{(t-t_k)}{t} \hat{g}_i(t_k) \quad (i = 1, 2)$$

converge as $t \to \infty$. So, by (2.7) and (2.8), we get

$$\frac{A(t)}{t} + B(t) = \frac{A(t_0)}{t} + B(t_0) + \int_{t_0}^{t} \frac{(t-s)}{t} \hat{f}(s) ds$$

$$+ \sum_{(t_0,t)} \frac{(t-t_k)}{t} \hat{g}_1(t_k) + \sum_{(t_0,t)} \frac{(t-t_k)}{t} \hat{g}_2(t_k)$$

Then $t^{-1} A(t) + B(t)$ converges at $t \to \infty$ and hence $t^{-1} A(t)$ converges also, i.e.,

$$A(t) = (\delta_1 + o(1)) t.$$

**Proof of Theorems 2 and 3.** From the proof of Theorem 1, we get that $t^{-1} y(t) = t^{-1} A(t) + B(t)$ and $y' = B$ converge as $t \to \infty$. Furthermore

$$\lim_{t \to \infty} \frac{y(t)}{t} = \lim_{t \to \infty} y'(t) \quad (2.12)$$

Let $y'(t_0) = y_1 \neq 0$. Then there exists $T$ large enough so that

$$| \int_{T}^{\infty} \hat{f}(s) ds + \sum_{(T, \infty)} \hat{g}_2(t_k) | < | y_1 | = | B(t_0) |$$

Thus (2.8) implies that $\lim_{t \to \infty} B(t) = \lim_{t \to \infty} y'(t) \neq 0$ and Theorem 2 follows from (2.12).

Finally, Theorem 3 follows at once from

$$t(y'(t) - \delta_2) = t(\int_{t}^{\infty} \hat{f}(s) ds + \sum_{(t, \infty)} \hat{g}_2(t_k))$$

$$\leq \int_{t}^{\infty} s \hat{f}(s) ds + \sum_{(t, \infty)} \hat{g}_2(t_k) \to 0 \quad \text{as} \quad t \to \infty$$

because of condition (T') implies $s \hat{f}(s) \in L_1$ and $t_k \hat{g}_2(t_k) \in \ell_1$. In this case, by (2.7) $A(t)$ itself converges as $t \to \infty$ and in the same way as it was proved previously we can demonstrate that there exist $A$ so that $A(\infty) \neq 0$, i.e., in formula (1.6), $\delta_1$ can be taken nonzero in this case.

**References**