CHAPTER -III
A NEUTRAL FUNCTIONAL
DIFFERENTIAL EQUATION IN
BANACH ALGEBRAS

3.1 Introduction
3.2 Statement of The Problem
3.3 Auxiliary Results
3.4 Existence Theory
3.5 Existence of Extremal Solutions
3.6 An Example

The contents of this chapter have been published in
3.1 Introduction

In this chapter an existence theorem for the first order functional differential equations in Banach algebras is proved under the mixed generalized Lipschitz and Caratheodory conditions. The existence of extremal solutions is also proved under certain monotonicity conditions.

3.2 Statement of Problem

Let $\mathbb{R}$ denote the real line and let $I_0 = [-r, 0]$ and $I = [0, a]$ be two closed and bounded intervals in $\mathbb{R}$. Let $J = I_0 \cup I$, then $J$ is a closed and bounded interval in $\mathbb{R}$. Let $C$ denote the Banach space of all continuous real-valued functions $\varphi$ on $I_0$ with the supremum norm $\| \cdot \|_C$ defined by

$$\| \varphi \|_C = \sup_{t \in I_0} |\varphi(t)|.$$

Clearly $C$ is a Banach algebra with this norm. Consider the first order functional differential equation (in short FDE)

$$\frac{d}{dt} \left[ \frac{\nu(t)}{f(t, x(t), x_t)} \right] = g(t, x(t), x_t) \quad a.e. \ t \in I \right)$$

$$\nu(t) = \varphi(t), \ t \in I_0.$$

(3.2.1)
Where \( f : I \times \mathbb{R} \times C \to \mathbb{R} - \{0\} \), \( g : I \times \mathbb{R} \times C \to \mathbb{R} \) and for each \( t \in I \), \( x_t : I_0 \to C \) is a continuous function defined by \( x_t(\theta) = x(t + \theta) \) for all \( \theta \in I_0 \).

By a solution of FDE (3.2.1) we mean a function

\[
\begin{align*}
x \in C(\ I, \mathbb{R}) \cap AC(\ I, \mathbb{R}) \cap C(\ I_0, \mathbb{R})
\end{align*}
\]

that satisfies the equations in (3.2.1), where \( AC(I, \mathbb{R}) \) is the space of all absolutely continuous real-valued functions on \( J \).

The functional differential equations have been the most active area of research since long time. See Hale (1977), Henderson (1995) and the references therein. But the study of functional differential equations in Banach algebra is very rare in the literature. Very recently the study along this line has been initiated via fixed point theorems. See Dhage and Regan (2000) and Dhage (1999) and the references therein. The FDE (3.2.1) is new to the literature and the study of this problem will definitely contribute immensely to the area of functional differential equations. The fixed point theorem that will be used is given in the following section.
3.3 Auxiliary Results

Let $X$ be a Banach algebra with norm $\|\cdot\|$. A mapping $A : X \to X$ is called $D$-Lipschitz if there exists a continuous nondecreasing function $\psi : \mathbb{R}^+ \to \mathbb{R}^+$ satisfying

$$\| Ax - Ay \| \leq \psi \| x - y \| \quad (3.3.1)$$

for all $x, y \in X$ with $\psi(0) = 0$. In the special case when $\psi(r) = \alpha r$ ($\alpha > 0$), $A$ is called a Lipschitz with a Lipschitz constant $\alpha$. In particular, if $\alpha < 1$, $A$ is called a contraction with a contraction constant $\alpha$. Further, if $\psi(r) < r$ for all $r > 0$, then $A$ is called a nonlinear contraction on $X$. Sometimes we call the function $\psi$ a $D$-function for convenience.

An operator $T : X \to X$ is called compact if $\overline{T(X)}$ is a compact subset of $X$. Similarly $T : X \to X$ is called totally bounded if $T$ maps a bounded subset of $X$ into the relatively compact subset of $X$. Finally $T : X \to X$ is called completely continuous operator if it is continuous and totally bounded operator on $X$. It is clear that every compact
operator is totally bounded, but the converse may not be true. The nonlinear alternative of Schaefer type recently proved by Dhage (2005-c) is embodied in the following theorem.

**Theorem 3.3.2** (Dhage, 2005-c) Let $X$ be a Banach algebra and let $A, B : X \rightarrow X$ be two operators satisfying

(a) $A$ is a $\mathcal{D}$-Lipschitz with a $\mathcal{D}$-function $\psi$,

(b) $B$ is compact and continuous, and

(c) $M \psi (r) < r$ whenever $r > 0$, where

$$M = \| B( X) \| = \sup\{ Bx \| x \in X\},$$

then either

(i) the equation $\lambda A \left(\frac{X}{\lambda}\right) B \lambda X = X$ has a solution for $\lambda = 1$, or

(ii) the set $\mathcal{E} = \{ u \in X \mid \lambda A \left(\frac{X}{\lambda}\right) Bu = u, \ 0 < \lambda < 1 \}$ is unbounded.

It is known that Theorem 3.3.2 useful for proving the existence theorems for the integral equations of mixed type. See Dhage (1994) and the references therein. The method is commonly known as *priori bound* method for the nonlinear equations. See, for example, Dugundji et.al. (1982), Zeidler (1985-b) and the references therein.
An interesting corollary to Theorem (3.3.2) in its applicable form is corollary 3.3.3 Let \( X \) be a Banach algebra and let \( A, B : X \to X \) be two operators satisfying.

(a) \( A \) is Lipschitz with a Lipschitz constant \( \alpha \),

(b) \( B \) is compact and continuous, and

(c) \( \alpha M < 1 \), where \( M = \| B(X) \| := \sup \{ \| Bx \| : x \in X \} \),

then either

(i) the equation \( \lambda A \left( \frac{1}{\lambda} \right) B = \chi \) has a solution for \( \lambda = 1 \), or

(ii) the set \( \mathcal{S} = \{ u \in X | \lambda A \left( \frac{1}{\lambda} \right) B u - u, 0 < \lambda < 1 \} \)

is unbounded.

### 3.4 Existence Theory

Let \( M(J, \mathbb{R}) \) and \( B(I, \mathbb{R}) \) respectively denote the spaces of measurable and bounded real-valued functions on \( J \). We shall seek the existence of a solution of FDE (3.2.1) in the space \( C(J, \mathbb{R}) \), of all absolutely continuous real-valued functions on \( J \). Define a norm \( \| \cdot \| \) in \( C(J, \mathbb{R}) \) by
Clearly $C(J, \mathbb{R})$ becomes a Banach algebra with this norm. Notice that $C(J, \mathbb{R}) \subseteq AC(J, \mathbb{R})$.

We need the following definition in the sequel.

**Definition 3.4.1** A mapping $\beta : I \times \mathbb{R} \times C \to \mathbb{R}$ is said to satisfy the condition of Caratheodory or simply said to be Caratheodory if

(i) $t \mapsto \beta(t, x, y)$ is measurable for each $x \in C$, and

(ii) $x \mapsto \beta(t, x, y)$ is continuous almost everywhere for $t \in I$.

Again a Caratheodory function $\beta(t, x, y)$ is called $L^1$-Caratheodory if

(iii) for each real number $r > 0$ there exists a function $h_r \in L^1(I, \mathbb{R})$ such that

$$|\beta(t, x, y)| = h_r(t), \text{ a.e. } t \in I.$$ for all $x \in \mathbb{R}$ and $y \in C$ with $|x| \leq r$ and $\|y\|_C \leq r$.

Finally a Caratheodory function $\beta(t, x, y)$ is called $L^1_N$-Caratheodory if

(iv) there exists a function $h \in L^1_N(I, \mathbb{R})$ such that

$$|\beta(t, x, y)| \leq h(t), \text{ a.e. } t \in I.$$
for all \( x \in \mathbb{R} \) and \( y \in \mathcal{C} \).

For convenience, the function \( h \) is referred to as a bound function of \( \beta \).

We will need the following hypotheses in the sequel.

\( \text{(H1)} \) The function \( f : I \times \mathbb{R} \times \mathcal{C} \to \mathbb{R} \) is continuous and there exists a function \( k \in B(I, \mathbb{R}) \) such that \( k(t) > 0 \), a.e. \( t \in I \) and
\[
|f(t, x_1, y_1) - f(t, x_2, y_2)| \leq k(t) \max\{|x_1 - x_2|, \|y_1 - y_2\|_c\} \text{ a.e. } t \in I
\]
for all \( x_1, x_2 \in \mathbb{R} \).

\( \text{(H2)} \) \( f(0, 0, 0) = 1 \).

\( \text{(H3)} \) The function \( g \) is \( L^1 \)-Carathéodory with bound function \( h \).

\( \text{(H4)} \) There exists a continuous and nondecreasing function
\[
\Omega : [0, \infty) \to (0, \infty)
\]
and a function \( \gamma \in L^1(I, \mathbb{R}) \) such that \( \gamma(t) > 0 \), a.e. \( t \in J \) and
\[
|g(t, x, y)| \leq \gamma(t) \Omega \max\{|x|, \|y\|_c\}, \text{ a.e. } t \in I,
\]
for all \( x \in \mathcal{C} \).

**Theorem 3.4.2** Assume that the hypotheses \( (H_1)-(H_4) \) hold. Suppose that

\[
\int_{C_2}^{C_2} \frac{ds}{\Omega(s)} > C_2 \| \gamma \|_p,
\]

\((3.4.3)\)
Where
\[ C_1 = \frac{F \| \emptyset \|_C}{1 - \| k \| (\| \emptyset \|_C + \| h \|_C)} , \quad C_2 = \frac{1}{1 - \| k \| (\| \emptyset \|_C + \| h \|_C)} , \]

then the \( FDE \) (3.2.1) has a solution on \( J \).

**Proof.** Now the \( FDE \) (3.2.1) is equivalent to the functional integral equation (in short FIE)
\[ x(t) = f[t, x(t), x_e] \left( \emptyset(0) + \int_0^t g(s, x(s), x_e) \, ds \right) , \quad \text{if} \ t \in I. \] (3.4.4)

and
\[ x(t) = \emptyset(t), \quad \text{if} \ t \in I_0. \] (3.4.5)

Define the two mappings \( A \) and \( B \) on \( C(J, \mathbb{R}) \) by
\[ A x(t) = \begin{cases} f(t, x(t), x_e) , & \text{if} \ t \in I. \\ 1 , & \text{if} \ t \in I_0, \end{cases} \] (3.4.6)

and
\[ B x(t) = \begin{cases} \emptyset(0) + \int_0^t g(s, x(s), x_e) \, ds , & \text{if} \ t \in I. \\ \emptyset(t) , & \text{if} \ t \in I_0. \end{cases} \] (3.4.7)
Obviously $A$ and $B$ define the operators $A, B : C(J, \mathbb{R}) \rightarrow C(J, \mathbb{R})$. Then the FDE (3.2.1) is equivalent to the operator equation

$$x(t) = Ax(t) + Bx(t), t \in J. \tag{3.4.8}$$

We shall show that the operators $A$ and $B$ satisfy all the hypotheses of Corollary (3.3.3).

We first show that $A$ is a Lipschitz on $C(J, \mathbb{R})$. Let $x, y \in C(J, \mathbb{R})$. Then by (H1),

$$|Ax(t) - Ay(t)| \leq |f(t, x(t), x_t) - f(t, y(t), y_t)|$$

$$\leq k(t) \max \{|x(t) - y(t)|, \|x_t - y_t\|_c\}$$

$$\leq k \|x - y\|$$

for all $t \in J$. Taking the supremum over $t$ we obtain

$$\|Ax - Ay\| \leq k \|x - y\|$$

for all $x, y \in C(J, \mathbb{R})$. So $A$ is a Lipschitz on $C(J, \mathbb{R})$ with a Lipschitz constant $\|k\|$. Next we show that $B$ is completely continuous on $C(J, \mathbb{R})$. Using the standard arguments as in Granas et al. (1991), it is shown that $B$ is a continuous operator on $C(J, \mathbb{R})$. Let $S$ be a bounded set in $C(J, \mathbb{R})$. We shall show that $B(C(J, \mathbb{R}))$ is a uniformly bounded and equicontinuous set in $C(J, \mathbb{R})$. Since $g(t, x(t), x_t)$ is $L^1_\infty$-Caratheodory, we have
Taking the supremum over \( t \), we obtain \( \|Bx\| \leq M \) for all \( x \in S \), where \( M = \| \varnothing \|_C + \| h \|_L^1 \). This shows that \( B(C(J, \mathbb{R})) \) is a uniformly bounded set in \( C(J, \mathbb{R}) \). Now we show that \( B(C(J, \mathbb{R})) \) is an equicontinuous set. Let \( t, \tau \in I \). Then for any \( x \in C(J, \mathbb{R}) \) we have by (3.4.6),

\[
|Bx(t) - Bx(\tau)| \leq \left| \int_0^t g(s, x(s), x_2) \, ds - \int_0^\tau g(s, x(s), x_2) \, ds \right| \\
\leq \left| \int_\tau^t |g(s, x(s), x_2)| \, ds \right| \\
\leq \left| \int_\tau^t h(s) \, ds \right| \\
\leq |p(\tau) - p(t)|
\]

where

\[
p(t) = \int_0^t h(s) \, ds.
\]

Therefore

\[
|Bx(t) - Bx(\tau)| \to 0 \text{ as } t \to \tau.
\]
Again let $\tau \in I_0$, $t \in I$. Then we obtain
\[
|Bx(t) - Bx(\tau)| \leq |\theta(\tau) - \theta(0)| + \left| \int_{0}^{t} g(s, x(s), x_2) \, ds \right|
\]
where the function $p$ is defined above. Similarly if $\tau, t \in I_0$, then we get
\[
|Bx(t) - Bx(\tau)| \leq |\theta(t) - \theta(\tau)|.
\]
Therefore in all above three cases
\[
|Bx(t) - Bx(\tau)| \to 0 \quad \text{as} \quad \tau \to t, \quad \forall \tau, t \in I.
\]
Hence $B(C(J, \mathbb{R}))$ is an equicontinuous set and consequently $B(C(J, \mathbb{R}))$ is relatively compact by Arzela-Ascoli theorem. As a result $B$ is a compact and continuous operator on $C(J, \mathbb{R})$. Thus all the conditions of Theorem (3.3.2) are satisfied and a direct application of it yields that either the conclusion (i) or the conclusion (ii) holds. We show that the conclusion (ii) is not possible. Let $x \in X$ be any solution to FDE (3.2.1). Then we have, for any $\lambda \in (0, 1)$,
\[
x(t) = \lambda A \left( \frac{\tau}{\lambda} \right)(t) Bx(t)
\]
\[
= \begin{cases} 
\lambda \int f \left( t, \frac{\lambda x(t)}{\lambda}, \frac{x_2}{\lambda} \right) \left( \phi(0) + \int_{0}^{t} g(s, x(s), x_2) \, ds \right), & t \in I \\
\lambda \phi(t), & t \in I_0
\end{cases}
\]
for $t \in J$. So if $t \in I_0$, then we have

57
\[ |x(t)| \leq \lambda \| \mathcal{O} \|_C \leq \| \mathcal{O} \|_C. \]

Again if \( t \in I \), then we have

\[
|\hat{x}(t)| \leq \lambda \left| f \left( \frac{s - x(t)}{\hat{x}}, \frac{x(t)}{\hat{x}} \right) \right| \left( \| \mathcal{O} \|_C + \int_0^t \mathcal{G}(s, x(s), x_2) \, ds \right)
\]

\[
\leq \lambda \left( \left| f \left( c, \frac{x(t)}{\hat{x}} \right) - f(c, 0, 0) \right| + |f(c, 0, 0)| \right)
\times \left( \| \mathcal{O} \|_C + \int_0^t \mathcal{G}(s, x(s), x_2) \, ds \right)
\]

\[
\leq k(t) \max \left\{ |x(t)|, \| x_2 \|_C \right\} \left( \| \mathcal{O} \|_C + \int_0^t \mathcal{G}(s, x(s), x_2) \, ds \right)
\]

\[
+ F \left( \| \mathcal{O} \|_C + \int_0^t \mathcal{G}(s, x(s), x_2) \, ds \right)
\]

\[
\leq k \| \mathcal{O} \|_C \max \left\{ |x(t)|, \| x_2 \|_C \right\} \left( \| x_2 \|_C + \| \mathcal{O} \|_C \right)
\]

\[
+ F \int_0^t \psi(s) \Omega \left( \max \left\{ |x(t)|, \| x_2 \|_C \right\} \right) \, ds.
\] \quad (3.4.9)

Put \( u(t) = \sup_{s \in [-r, t]} |x(s)| \), for \( t \in J \). Then we have \( \max\{ |x(t)|, \| x_2 \|_C \} \leq u(t) \) for all \( t \in J \), and so, there is a point \( t^* \in [-r, t] \) such that \( u(t) = |x(t^*)| \). From (3.4.9) it follows that

\[ u(t) = |x(t^*)| \]
\[ \begin{align*}
\leq & \| h \| \| \phi \nu \| (\| \phi \|_c + \| h \|_\nu) \\
  & + \mathcal{F} \left( \| \phi \|_c \int_0^t \gamma(s) \Omega(\max(x(t), \| x \|_c)) \, ds \right) \\
\leq & \| h \| \| \nu \| (\| \phi \|_c + \| h \|_\nu) + \mathcal{F} \left( \| \phi \|_c \int_0^t \gamma(s) \Omega(u(s)) \, ds \right) \\
  & = C_1 + C_2 \int_0^t \gamma(s) \Omega(u(s)) \, ds \\
\end{align*} \]  

(3.4.10)

Where

\[ C_1 = \frac{\mathcal{F} \| \phi \|_c}{1 - \| h \| \| \phi \|_c + \| h \|_\nu} \quad \text{and} \quad C_2 = \frac{1}{1 - \| h \| \| \phi \|_c + \| h \|_\nu} \]

Let

\[ \omega(t) = C_1 + C_2 \int_0^t \gamma(s) \Omega(u(s)) \, ds. \]

Then \( u(t) \leq \omega(t) \) and a direct differentiation of \( \omega(t) \) yields

\[ \begin{align*}
\omega'(t) & \leq C_2 \gamma(t) \Omega(\omega(t)) \\
\omega(0) & = C_1
\end{align*} \]  

(3.4.11)

that is

\[ \int_0^t \frac{\omega'(s)}{\Omega(\omega(s))} \, ds \leq C_2 \int_0^t \gamma(s) \, ds \leq C_2 \| \gamma \| \nu. \]

A change of variables in the above integral gives that
Now an application of mean value theorem yields that there is a constant $M > 0$ such that $\omega(t) \leq M$ for all $t \in J$. This further implies that

$$|\kappa(t)| \leq u(t) \leq \omega(t) \leq M,$$

for all $t \in J$. Thus the conclusion (ii) of Corollary (3.3.3) does not hold. Therefore the operator equation $Ax = x$ and consequently the FDE (3.2.1) has a solution on $J$. This completes the proof.

### 3.5 Existence of Extremal Solutions

A non-empty closed set $K$ in a Banach algebra $X$ is called a cone if (i) $K + K \subseteq K$, (ii) $\lambda K \subseteq K$ for $\lambda \in \mathbb{R}$, $\lambda \geq 0$ and (iii) $\{-K\} \cap K = 0$, where $0$ is the zero element of $X$. A cone $K$ is called to be positive if (iv) $K \circ K \subseteq K$, where "$\circ$" is a multiplication composition in $X$. We introduce an order relation $\leq$ in $K$ as follows. Let $x, y \in X$. Then $x \leq y$ if and only if $y - x \in K$. A cone $K$ is called to be normal if the norm $\|\cdot\|$ is monotone increasing on $K$. It is known that if the cone $K$ is normal in $X$, then every order-bounded set in $X$ is norm-
bounded. The details of cones and their properties appear in Guo et al. (1988).

We equip the space $C(J, \mathbb{R})$ with the order relation $\leq$ with the help of the cone defined by

$$K = \{x \in C(J, \mathbb{R}) | x(t) \geq 0, \forall t \in J\}. \quad (3.5.1)$$

It is well known that the cone $K$ is positive and normal in $C(J, \mathbb{R})$. As a result of positivity of the cone $K$ in $C(J, \mathbb{R})$ we have:

**Lemma 3.5.2** (Dhage, 1999). Let $u_1, u_2, v_1, v_2 \in K$ be such that $u_1 \leq v_1$ and $u_2 \leq v_2$. Then $u_1u_2 \leq v_1v_2$.

For any $a, b \in X = C(J, \mathbb{R})$, $a \leq b$, the order interval $[a, b]$ is a set in $X$ given by

$$[a, b] = \{x \in X | a \leq x \leq b\}.$$

We use the following fixed point theorem of Dhage (1999) for proving the existence of extremal solutions of the FDE (3.2.1) under certain monotonicity conditions.

**Theorem 3.5.3** (Dhage (1999), Corollary). Let $K$ be a cone in a Banach algebra $X$ and let $a, b \in X$. Suppose that $A, B : [a, b] \to K$ are two operators such that
(a) $A$ is Lipschitz with a Lipschitz constant $\alpha$,
(b) $B$ is completely continuous,
(c) $Ax \leq Bx \in [a, b]$ for each $x \in [a, b]$, and
(d) $A$ and $B$ are nondecreasing.

Further if the cone $K$ is positive and normal, then the operator equation $Ax \leq Bx = x$ has a maximal and a minimal positive solution in $[a, b]$, whenever $\alpha M < 1$, where

$$M = \|B\| ([a, b]) \|: = \sup \{\|Bx\| : x \in [a, b]\}.$$ 

We need the following definitions in the sequel.

**Definition 3.5.4** A function $u \in C(J, \mathbb{R})$ is called a lower solution of the FDE (3.2.1) on $J$ if

\[
\frac{d}{dt} \left[ \frac{u(t)}{f(r, u(t), u')} \right] \geq g(t, u(t), u'), \quad a.s. t \in I
\]

and

$$u(t) \leq \phi(t) \text{ for all } t \in I_0.$$ 

Again a function $v \in C(J, \mathbb{R})$ is called an upper solution of the BVP (3.2.1) on $J$ if

\[
\frac{d}{dt} \left[ \frac{v(t)}{f(r, v(t), v')} \right] \geq g(t, v(t), v'), \quad a.s. t \in I
\]
and

\[ \psi(t) \equiv \phi(t) \quad \text{for all } t \in I_0. \]

**Definition 3.5.5** A solution \( x_M \) of the FDE \((3.2.1)\) is said to be maximal if for any other solution \( x \) to FDE(3.2.1) one has \( x(t) \leq x_M(t), \forall \ t \in J. \) Again a solution \( x_m \) of the FDE \((3.2.1)\) is said to be minimal if \( x_m(t) \leq x(t), \forall \ t \in J, \) where \( x \) is any solution of the FDE \((3.2.1)\) on \( J. \)

We consider the following set of assumptions:

\((B_0)\) \( f : J \times \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}^+ - \{0\}, \ g : J \times \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}^+ \) and \( \phi(0) \geq 0. \)

\((B_1)\) \( g \) is \( L^1 \)-Carathéodory.

\((B_2)\) The functions \( f(t, x, y) \) and \( g(t, x, y) \) are non-decreasing in \( x \) and \( y \) almost everywhere for \( t \in J. \)

\((B_3)\) The FDE \((3.2.1)\) has a lower solution \( u \) and an upper solution \( v \) on \( J \) with \( u \leq v. \)

**Remark 3.5.6** Assume that \((B_1)-(B_3)\) hold. Define a function \( h : J \rightarrow \mathbb{R}^+ \) by

\[ \vartheta(t) = |g(t, u(t), u(c))| + |g(t, v(t), v(c))|, \forall t \in I. \]

Then \( h \) is Lebesgue integrable and

\[ |g(t, x(t), x(c))| \leq f(t), \ a.e. \ t \in I, \]

for all \( x \in [u, v]. \)
Theorem 3.5.7  Suppose that the assumptions \((H_1)-(H_3)\) and \((B_0)-(B_3)\) hold. Further if \(\|h\| \left( \|\mathcal{O}\|_C + \|f\|_{L^1} \right) < 1\) and \(h\) is given in Remark (3.5.6), then FDE (3.2.1) has a minimal and a maximal positive solution on \(J\).

Proof. Now FDE (3.2.1) is equivalent to FIE (3.4.4)-(3.4.5) on \(J\). Let \(X = C(J, \mathbb{R})\). Define two operators \(A\) and \(B\) on \(X\) by (3.4.6) and (3.4.7) respectively. Then FIE (3.2.1) is transformed into an operator equation \(Ax(t)Bx(t) = x(t)\) in a Banach algebra \(X\). Notice that \((B_1)\) implies \(A, B : [u, v] \to K\). Since the cone \(K\) in \(X\) is normal, \([u, v]\) is a norm bounded set in \(X\). Now it is shown, as in the proof of Theorem (3.4.2), that \(A\) is a Lipschitz with a Lipschitz constant \(\|a\|\) and \(B\) is completely continuous operator on \([u, v]\). Again the hypothesis \((B_2)\) implies that \(A\) and \(B\) are nondecreasing on \([u, v]\). To see this, let \(x, y \in [u, v]\) be such that \(x \leq y\). Then by \((B_2)\),

\[ Ax(t) = f(t, x(t), x_t) \leq f(t, y(t), y_t) = Ay(t), \quad \forall t \in I, \]

and

\[ Ax(t) = 1 = Ay(t), \quad \text{for all } t \in I_0. \]
Similarly

\[ Bx(t) = \Theta(0) + \int_0^t g(s, x(s), x_2) \, ds \]

\[ \leq \Theta(0) + \int_0^t g(s, x(s), y_2) \, ds \]

\[ = Ay(t), \forall t \in I. \]

and

\[ Bx(t) = \Theta(t) = By(t) \quad \text{for all} \quad t \in I_2. \]

So \( A \) and \( B \) are nondecreasing operators on \([u, v]\). Again Lemma (3.5.2) and hypothesis (B₃) implies that

\[ u(t) \leq [f(t, u(t), u_x)]\left(\Theta(0) \int_0^t g(s, u(s), u_x) \, ds\right) \]

\[ \leq [f(t, u(t), u_x)]\left(\Theta(0) \int_0^t g(s, x(s), x_x) \, ds\right) \]

\[ \leq [f(t, v(t), v_x)]\left(\Theta(0) \int_0^t g(s, v(s), v_x) \, ds\right) \]

\[ \leq v(t) \]

for all \( t \in I \) and \( x \in [u, v] \). As a result \( u(t) \leq Ax(t) Bx(t) \leq v(t), \forall t \in J \) and \( x \in [u, v] \). Hence \( Ax \, Bx \in [u, v], x \in [u, v] \).
Again,

\[
M = \| B([u,v]) \| = \sup \{ \| Bx \| : x \in [u,v] \} \\
= \sup \left\{ \| \varnothing \|_{c^1} \right\} + \sup_{t \in I} \int_0^t \left| g(s,x(s),x_2) \right| \, ds : x \in [u,v] \}
\]

\[
\leq \| \varnothing \|_{c^1} + \int_0^a \| f(s) \| \, ds
\]

Since \( \alpha M \leq \| k \| (\| \varnothing \|_{c^1} + \| f \|_{L^1}) < 1 \), we apply Theorem (3.5.3) to the operator equation \( Ax(t)Bx(t) = x \) to yield that the FDE (3.2.1) has a minimal and a maximal positive solution on \( J \). This completes the proof.

### 3.6 An Example

Given the closed and bounded intervals

\( I_0 = [-\pi/2, 0] \) and \( I = [0, \pi /2] \) in \( \mathbb{R} \), consider the nonlinear FDE

\[
\begin{bmatrix}
\frac{d}{dc} & \left( \frac{x(c)}{f(c,x(c),x_2)} \right) \\
\frac{d}{dc} & \left( \frac{x_2(c)}{f(c,x(c),x_2)} \right)
\end{bmatrix} = \frac{p(c)x}{1+\| x_2 \|_c} \quad \text{a.s.} \quad c \in I
\]

\[
x(c) = \sin c, \quad c \in I_0
\]

where \( p \in L^1(I, \mathbb{R}) \) and \( f : I \times \mathbb{R} \times C \to \mathbb{R} \) is defined by
\[
f(t, x(t), x_{\alpha}) = \frac{1}{2}[1 + \alpha |x(t)| + \|x_{\alpha}\| \alpha > 0
\]
for all \( t \in I \). Obviously \( f : I \times \mathbb{R} \times \mathbb{C} \rightarrow \mathbb{R}^+ - \{0\} \). Define a function

\[
g : I \times C \rightarrow \mathbb{R}
\]
by

\[
g(t, x(t), x_{\alpha}) = \frac{p(t)x(t)}{1 + |x(t)| + \|x_{\alpha}\|}
\]

It is easy to verify that \( f \) is continuous and Lipschitz on \( J \times \mathbb{R} \) with a Lipschitz constant \( \alpha \). Further \( g(t, x, y) \) is \( L^1 \)-Carathéodory with the bound function \( h(t) = p(t) \) on \( I \). Therefore if \( \alpha \left(1 + \|p\|_{L^1}\right) < 1/2 \), then by Theorem (3.4.2), the FDE (3.6.1) has a solution on \( J \), because the function \( \Omega \) satisfies condition (3.4.3) with \( \gamma(t) = p(t) \) for all \( t \in I \) and \( \Omega (r) = 1 \) for all \( r \in \mathbb{R}^+ \).