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h-STABILITY AND BOUNDEDNESS IN THE PERTURBED FUNCTIONAL DIFFERENTIAL SYSTEMS

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Abstract. In this paper, we investigate h-stability and bounds for solutions of the the functional perturbed differential systems.

1. Introduction

Integral inequalities play a vital role in the study of boundedness and other qualitative properties of solutions of differential equations. The behavior of solutions of a perturbed system is determined in terms of the behavior of solutions of an unperturbed system. There are three useful methods for showing the qualitative behavior of the solutions of perturbed nonlinear system : the use of integral inequalities, the method of variation of constants formula, and Lyapunov's second method.

The notion of h-stability (hS) was introduced by Pinto [13,14] with the intention of obtaining results about stability for a weakly stable system (at least, weaker than those given exponential asymptotic stability) under some perturbations. He obtained a general variational h-stability and some properties about asymptotic behavior of solutions of differential systems called h-systems. Also, he studied some general results about asymptotic integration and gave some important examples in [14]. Choi and Koo [2], Choi and Ryu [3], and Choi et al. [4,5] investigated h-stability and bounds of solutions for the perturbed functional differential systems. Also, Goo et al. [7,8,9] studied the boundedness of solutions for the perturbed functional differential systems.

The aim of this paper is to obtain h-stability and some results on boundedness of the functional perturbed differential systems under suitable conditions on perturbed term. To do this, we need some integral inequalities.

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2. Preliminaries

We consider the nonlinear differential system

$$x'(t) = f(t, x(t)), \quad x(t_0) = x_0, \tag{2.1}$$

where $f \in C(\mathbb{R}^+ \times \mathbb{R}^n, \mathbb{R}^n)$, $\mathbb{R}^+ = [0, \infty)$ and $\mathbb{R}^n$ is the Euclidean n-space. We assume that the Jacobian matrix $f_x = \partial f/\partial x$ exists and is continuous on $\mathbb{R}^+ \times \mathbb{R}^n$ and $f(t, 0) = 0$. Also, consider the perturbed differential systems of (2.1)

$$y' = f(t, y) + \int_{t_0}^{t} g(s, y(s))ds + h(t, y(t), Ty(t)),\ y(t_0) = y_0, \tag{2.2}$$

where $g \in C(\mathbb{R}^+ \times \mathbb{R}^n, \mathbb{R}^n)$, $h \in C[\mathbb{R}^+ \times \mathbb{R}^n \times \mathbb{R}^n, \mathbb{R}^n]$, $g(t, 0) = 0$, $h(t, 0, 0) = 0$, and $T : C(\mathbb{R}^+, \mathbb{R}^n) \to C(\mathbb{R}^+, \mathbb{R}^n)$ is a continuous operator. For $x \in \mathbb{R}^n$, let $|x| = (\sum_{j=1}^{n} x_j^2)^{1/2}$. For an $n \times n$ matrix A, define the norm $|A|$ of A by $|A| = \sup_{|x| \le 1} |Ax|$.

Let $x(t, t_0, x_0)$ denote the unique solution of (2.1) with $x(t_0, t_0, x_0) = x_0$, existing on $[t_0, \infty)$. Also, we consider the associated variational systems around the zero solution of (2.1) and around $x(t)$, respectively,

$$v'(t) = f_x(t, 0)v(t),\ v(t_0) = v_0 \tag{2.3}$$

and

$$z'(t) = f_x(t, x(t, t_0, x_0))z(t),\ z(t_0) = z_0. \tag{2.4}$$

The fundamental matrix $\Phi(t, t_0, x_0)$ of (2.4) is given by

$$\Phi(t, t_0, x_0) = \frac{\partial}{\partial x_0} x(t, t_0, x_0),$$

and $\Phi(t, t_0, 0)$ is the fundamental matrix of (2.3).

We recall some notions of h-stability [14].

Definition 2.1. The system (2.1) (the zero solution $x = 0$ of (2.1)) is called
(hS)*h-stable* if there exist a constant $c \ge 1$, and a positive bounded continuous function h on $\mathbb{R}^+$ such that

$$|x(t)| \le c\,|x_0|\,h(t)\,h(t_0)^{-1}$$

for $t \ge t_0 \ge 0$ and $|x_0| \le \delta$ (here $h(t)^{-1} = \frac{1}{h(t)}$).

Let $\mathcal{M}$ denote the set of all $n \times n$ continuous matrices $A(t)$ defined on $\mathbb{R}^+$ and $\mathcal{N}$ be the subset of $\mathcal{M}$ consisting of those nonsingular matrices $S(t)$ that are of class C^1 with the property that $S(t)$ and $S^{-1}(t)$ are bounded. The notion of t_∞-similarity in $\mathcal{M}$ was introduced by Conti [6].

Definition 2.2. A matrix $A(t) \in \mathcal{M}$ is *t_∞-similar* to a matrix $B(t) \in \mathcal{M}$ if there exists an $n \times n$ matrix $F(t)$ absolutely integrable over $\mathbb{R}^+$, i.e.,

$$\int_0^\infty |F(t)|dt < \infty$$

such that

$$\dot{S}(t) + S(t)B(t) - A(t)S(t) = F(t) \tag{2.5}$$

for some $S(t) \in \mathcal{N}$.

The notion of t_∞-similarity is an equivalence relation in the set of all $n \times n$ continuous matrices on $\mathbb{R}^+$, and it preserves some stability concepts [4,10].

In this paper, we investigate hS and bounds for solutions of the functional perturbed differential systems using the notion of t_∞-similarity.

We give some related properties that we need in the sequal.

Lemma 2.3. [14]
The linear system

$$x' = A(t)x, \; x(t_0) = x_0, \tag{2.6}$$

where $A(t)$ is an $n \times n$ continuous matrix, is an h-system (respectively h-stable) if and only if there exist $c \geq 1$ and a positive and continuous (respectively bounded) function h defined on $\mathbb{R}^+$ such that

$$|\phi(t, t_0)| \leq c\, h(t)\, h(t_0)^{-1} \tag{2.7}$$

for $t \geq t_0 \geq 0$, where $\phi(t, t_0)$ is a fundamental matrix of (2.6).

We need Alekseev formula to compare between the solutions of (2.1) and the solutions of perturbed nonlinear system

$$y' = f(t, y) + g(t, y), \; y(t_0) = y_0, \tag{2.8}$$

where $g \in C(\mathbb{R}^+ \times \mathbb{R}^n, \mathbb{R}^n)$ and $g(t, 0) = 0$. Let $y(t) = y(t, t_0, y_0)$ denote the solution of (2.8) passing through the point (t_0, y_0) in $\mathbb{R}^+ \times \mathbb{R}^n$.

The following is a generalization to nonlinear system of the variation of constants formula due to Alekseev [1].

Lemma 2.4. *If $y_0 \in \mathbb{R}^n$, then for all t such that $x(t, t_0, y_0) \in \mathbb{R}^n$,*

$$y(t, t_0, y_0) = x(t, t_0, y_0) + \int_{t_0}^{t} \Phi(t, s, y(s))\, g(s, y(s))\, ds.$$

THEOREM 2.1. [3] *If the zero solution of (2.1) is hS, then the zero solution of (2.3) is hS.*

THEOREM 2.2. [4] *Suppose that $f_x(t,0)$ is t_∞-similar to $f_x(t,x(t,t_0,x_0))$ for $t \geq t_0 \geq 0$ and $|x_0| \leq \delta$ for some constant $\delta > 0$. If the solution $v = 0$ of (2.3) is hS, then the solution $z = 0$ of (2.4) is hS.*

LEMMA 2.5. ($Bihari - type\ inequality$ [5], 1956) *Let $u, \lambda \in C(\mathbb{R}^+)$, $w \in C((0,\infty))$ and $w(u)$ be nondecreasing in u. Suppose that, for some $c > 0$,*

$$u(t) \leq c + \int_{t_0}^{t} \lambda(s)w(u(s))ds,\ t \geq t_0 \geq 0.$$

Then

$$u(t) \leq W^{-1}\Big[W(c) + \int_{t_0}^{t} \lambda(s)ds\Big],\ t_0 \leq t < b_1,$$

where $W(u) = \int_{u_0}^{u} \frac{ds}{w(s)}$, $W^{-1}(u)$ is the inverse of $W(u)$ and

$$b_1 = \sup\Big\{t \geq t_0 : W(c) + \int_{t_0}^{t} \lambda(s)ds \in \mathrm{domW^{-1}}\Big\}.$$

LEMMA 2.6. [12] *Let $a, u \in C[\mathbb{R}^+, \mathbb{R}^+], b(t,s) \in C[\mathbb{R}^+ \times \mathbb{R}^+, \mathbb{R}^+]$ for $t_0 \leq s \leq t$ and $k \geq 0$ be constant. If*

$$u(t) \leq k + \int_{t_0}^{t} [a(s)u(s) + \int_{t_0}^{s} b(s,\tau)u(\tau)d\tau]ds,$$

for $t \in \mathbb{R}^+$, then

$$u(t) \leq k \exp\Big(\int_{t_0}^{t} [a(s) + \int_{t_0}^{s} b(s,\tau)d\tau]ds\Big),$$

for $t \in \mathbb{R}^+$.

3. Main results

In this section, we investigate hS and boundedness for solutions of the functional perturbed differential systems via t_∞-similarity.

THEOREM 3.1. *Suppose that $f_x(t,0)$ is t_∞-similar to $f_x(t,x(t,t_0,x_0))$ for $t \geq t_0 \geq 0$ and $|x_0| \leq \delta$ for some constant $\delta > 0$, the solution $x = 0$ of (2.1) is hS with the increasing function h, and g in (2.2) satisfies*

$$\int_{t_0}^{s} |g(\tau, y(\tau))|d\tau \leq a(s)|y(s)| + b(s)\int_{t_0}^{s} r(\tau)|y(\tau)|d\tau,$$

and

$$|h(s, y(s), Ty(s))| \le b(s)(|y(s)| + |Ty(s)|), |Ty(s)| \le \int_{t_0}^{s} q(\tau)|y(\tau)|d\tau,$$

where $a, b, q, r \in C(\mathbb{R}^+)$, $\int_{t_0}^{\infty} a(s)ds < \infty$, $\int_{t_0}^{\infty} b(s)ds < \infty$, $\int_{t_0}^{\infty} q(s)ds < \infty$, $\int_{t_0}^{\infty} r(s)ds < \infty$, *and* $\int_{t_0}^{\infty}[a(s)+b(s)+b(s)\int_{t_0}^{s}(r(\tau)+q(\tau))d\tau]ds < \infty$. *Then, any solution* $y = 0$ *of (2.2) is hS.*

Proof. Let $x(t) = x(t, t_0, y_0)$ and $y(t) = y(t, t_0, y_0)$ be solutions of (2.1) and (2.2), respectively. By Theorem 2.1, since the solution $x = 0$ of (2.1) is hS, the solution $v = 0$ of (2.3) is hS. Therefore, by Theorem 2.2, the solution $z = 0$ of (2.4) is hS. Using the nonlinear variation of constants formula and the hS condition of $x = 0$ of (2.1), we have

$$\begin{aligned}
|y(t)| &\le |x(t)| + \int_{t_0}^{t} |\Phi(t, s, y(s))| \Big(\int_{t_0}^{s} |g(\tau, y(\tau))|d\tau + |h(s, y(s), Ty(s))| \Big) ds \\
&\le c_1|y_0|h(t)\, h(t_0)^{-1} + \int_{t_0}^{t} c_2 h(t)h(s)^{-1}\Big((a(s) + b(s))|y(s)| \\
&\quad + b(s)\int_{t_0}^{s}(r(\tau) + q(\tau))|y(\tau)|d\tau\Big) ds \\
&\le c_1|y_0|h(t)\, h(t_0)^{-1} + \int_{t_0}^{t} c_2 h(t)(a(s) + b(s))\frac{|y(s)|}{h(s)} ds \\
&\quad + \int_{t_0}^{t} c_2 h(t)b(s)\int_{t_0}^{s}(r(\tau) + q(\tau))\frac{|y(\tau)|}{h(\tau)} d\tau ds.
\end{aligned}$$

Set $u(t) = |y(t)||h(t)|^{-1}$. Now an application of Lemma 2.6 yields

$$\begin{aligned}
&|y(t)| \\
&\le c_1|y_0|h(t)\, h(t_0)^{-1}| \exp\Big(c_2\int_{t_0}^{t}[a(s) + b(s) + b(s)\int_{t_0}^{s}(r(\tau) + q(\tau))d\tau]ds\Big) \\
&\le c|y_0|h(t)\, h(t_0)^{-1},
\end{aligned}$$

where $c = c_1 \exp\Big(c_2\int_{t_0}^{\infty}[a(s) + b(s) + b(s)\int_{t_0}^{s}(r(\tau) + q(\tau))d\tau]ds\Big)$. It follows that $y = 0$ of (2.2) is hS, and so the proof is complete. □

Remark 3.1. Letting $r(\tau) = 0$ in Theorem 3.1, we obtain the same result as that of Theorem 3.1 in [8].

Lemma 3.2. *Let* $u, \lambda_1, \lambda_2, \lambda_3, \lambda_4 \in C(\mathbb{R}^+)$, $w \in C((0, \infty))$ *and* $w(u)$ *be nondecreasing in* u, $u \le w(u)$. *Suppose that for some* $c > 0$, $0 \le t_0 \le t$,

$$u(t) \le c + \int_{t_0}^{t} \lambda_1(s)u(s)ds + \int_{t_0}^{t} \lambda_2(s)w(u(s))ds + \int_{t_0}^{t} \lambda_3(s)\int_{t_0}^{s} \lambda_4(\tau)u(\tau)d\tau ds.$$

Then

(3.1)

$$u(t) \le W^{-1}\Big[W(c) + \int_{t_0}^{t}(\lambda_1(s) + \lambda_2(s) + \lambda_3(s)\int_{t_0}^{s}\lambda_4(\tau)d\tau)ds\Big],\ t_0 \le t < b_1,$$

where W, W^{-1} are the same functions as in Lemma 2.5 and

$$b_1 = \sup\Big\{t \ge t_0 : W(c)+\int_{t_0}^{t}(\lambda_1(s)+\lambda_2(s)+\lambda_3(s)\int_{t_0}^{s}\lambda_4(\tau)d\tau)ds \in \mathrm{domW^{-1}}\Big\}.$$

Proof. Defining

$$z(t) = c+\int_{t_0}^{t}\lambda_1(s)u(s)ds+\int_{t_0}^{t}\lambda_2(s)w(u(s))ds+\int_{t_0}^{t}\lambda_3(s)\Big(\int_{t_0}^{s}\lambda_4(\tau)u(\tau)d\tau\Big)ds,$$

then we have $z(t_0) = c$ and

$$\begin{aligned} z'(t) &= \lambda_1(t)u(t) + \lambda_2(t)w(u(t)) + \lambda_3(t)\int_{t_0}^{t}\lambda_4(s)u(s)ds \\ &\le (\lambda_1(t) + \lambda_2(t) + \lambda_3(t)\int_{t_0}^{t}\lambda_4(s)ds)w(z(t)),\ t \ge t_0, \end{aligned}$$

since $z(t)$ and $w(u)$ are nondecreasing, $u \le w(u)$, and $u(t) \le z(t)$. Therefore, by integrating on $[t_0, t]$, the function z satisfies

$$z(t) \le c + \int_{t_0}^{t}(\lambda_1(s) + \lambda_2(s) + \lambda_3(s)\int_{t_0}^{s}\lambda_4(\tau)d\tau)w(z(s)))ds. \tag{3.2}$$

It follows from Lemma 2.5 that (3.2) yields the estimate (3.1). □

THEOREM 3.2. *Let $a, b, q, u, w \in C(\mathbb{R}^+)$, $w(u)$ be nondecreasing in u such that $u \le w(u)$ and $\frac{1}{v}w(u) \le w(\frac{u}{v})$ for some $v > 0$. Suppose that $f_x(t, 0)$ is t_∞-similar to $f_x(t, x(t, t_0, x_0))$ for $t \ge t_0 \ge 0$ and $|x_0| \le \delta$ for some constant $\delta > 0$, the solution $x = 0$ of (2.1) is hS with the increasing function h, and g in (2.2) satisfies*

$$\int_{t_0}^{s}|g(\tau, y(\tau))|d\tau \le a(s)w(|y(s)|),$$

and

$$|h(s, y(s), Ty(s))| \le b(s)(|y(s)|+|Ty(s)|), |Ty(s)| \le \int_{t_0}^{s}q(\tau)|y(\tau)|d\tau,\ s \ge t_0 \ge 0,$$

where $\int_{t_0}^{\infty}a(s)ds < \infty$, $\int_{t_0}^{\infty}b(s)ds < \infty$, and $\int_{t_0}^{\infty}q(s)ds < \infty$. Then, any solution $y(t) = y(t, t_0, y_0)$ of (2.2) is bounded on $[t_0,\infty)$ and it satisfies

$$|y(t)| \le h(t)W^{-1}\Big[W(c)+c_2\int_{t_0}^{t}(a(s)+b(s)+b(s)\int_{t_0}^{s}q(\tau)d\tau)ds\Big],\ t_0 \le t < b_1,$$

where $c = c_1|y_0|\,h(t_0)^{-1}$, W, W^{-1} *are the same functions as in Lemma 2.5 and*

$$b_1 = \sup\Big\{t \geq t_0 : W(c)+c_2\int_{t_0}^{t}(a(s)+b(s)+b(s)\int_{t_0}^{s} q(\tau)d\tau)ds \in \mathrm{domW}^{-1}\Big\}.$$

Proof. Let $x(t) = x(t, t_0, y_0)$ and $y(t) = y(t, t_0, y_0)$ be solutions of (2.1) and (2.2), respectively. By Theorem 2.1, since the solution $x = 0$ of (2.1) is hS, the solution $v = 0$ of (2.3) is hS. Therefore, by Theorem 2.2, the solution $z = 0$ of (2.4) is hS. By Lemma 2.3, Lemma 2.4 and the increasing property of the function h, we have

$$\begin{aligned}
|y(t)| &\leq |x(t)| + \int_{t_0}^{t} |\Phi(t,s,y(s))|\Big(\int_{t_0}^{s} |g(\tau,y(\tau))|d\tau + |h(s,y(s),Ty(s))|\Big)ds \\
&\leq c_1|y_0|h(t)\,h(t_0)^{-1} + \int_{t_0}^{t} c_2h(t)h(s)^{-1}\Big((a(s)w(|y(s)|) + b(s)(|y(s)| \\
&\quad + \int_{t_0}^{s} q(\tau)|y(\tau)|d\tau\Big)ds \\
&\leq c_1|y_0|h(t)\,h(t_0)^{-1} + \int_{t_0}^{t} c_2h(t)b(s)\frac{|y(s)|}{h(s)}ds \\
&\quad + \int_{t_0}^{t} c_2h(t)a(s)w(\frac{|y(s)|}{h(s)})ds + \int_{t_0}^{t} c_2h(t)b(s)\int_{t_0}^{s} q(\tau)\frac{|y(\tau)|}{h(\tau)}d\tau ds.
\end{aligned}$$

Set $u(t) = |y(t)||h(t)|^{-1}$. Then, by Lemma 3.2, we obtain

$$|y(t)| \leq h(t)W^{-1}\Big[W(c) + c_2\int_{t_0}^{t}(a(s) + b(s) + b(s)\int_{t_0}^{s} q(\tau)d\tau)ds\Big],$$

where $c = c_1|y_0|\,h(t_0)^{-1}$. Thus, any solution $y(t) = y(t, t_0, y_0)$ of (2.2) is bounded on $[t_0, \infty)$. This completes the proof. □

REMARK 3.3. Letting $w(u) = u$ in Theorem 3.2, we obtain the same result as that of Theorem 3.1 in [8].

LEMMA 3.4. *Let* $u, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \in C(\mathbb{R}^+)$, $w \in C((0,\infty))$ *and* $w(u)$ *be nondecreasing in* u, $u \leq w(u)$. *Suppose that for some* $c > 0$ *and* $0 \leq t_0 \leq t$,

$$\begin{aligned}
u(t) \leq c + \int_{t_0}^{t} \lambda_1(s)w(u(s))ds + \int_{t_0}^{t}\lambda_2(s)\Big(\int_{t_0}^{s}(\lambda_3(\tau)u(\tau) \\
+ \lambda_4(\tau)\int_{t_0}^{\tau} \lambda_5(r)w(u(r))dr)d\tau\Big)ds,
\end{aligned}$$

Then
(3.3)
$$u(t) \le W^{-1}\Big[W(c) + \int_{t_0}^{t}(\lambda_1(s) + \lambda_2(s)\int_{t_0}^{s}(\lambda_3(\tau) + \lambda_4(\tau)\int_{t_0}^{\tau}\lambda_5(r)dr)d\tau))ds\Big],$$

$t_0 \le t < b_1$, *where* W, W^{-1} *are the same functions as in Lemma 2.5 and*

$$b_1 = \sup\Big\{t \ge t_0 : W(c) + \int_{t_0}^{t}(\lambda_1(s)+\lambda_2(s)\int_{t_0}^{s}(\lambda_3(\tau) + \lambda_4(\tau)\int_{t_0}^{\tau}\lambda_5(r)dr)d\tau))ds \in \mathrm{domW^{-1}}\Big\}.$$

Proof. Setting

$$z(t) = c + \int_{t_0}^{t}\lambda_1(s)w(u(s))ds + \int_{t_0}^{t}\lambda_2(s)\Big(\int_{t_0}^{s}(\lambda_3(\tau)u(\tau) + \lambda_4(\tau)\int_{t_0}^{\tau}\lambda_5(r)w(u(r))dr)d\tau\Big)ds,$$

then we have $z(t_0) = c$ and

$$\begin{aligned} z'(t) \quad &= \lambda_1(t)w(u(t)) + \lambda_2(t)\textstyle\int_{t_0}^{t}(\lambda_3(s)u(s) + \lambda_4(s)\int_{t_0}^{s}\lambda_5(\tau)w(u(\tau))d\tau)ds \\ &\le (\lambda_1(t) + \lambda_2(t)\textstyle\int_{t_0}^{t}(\lambda_3(s) + \lambda_4(s)\int_{t_0}^{s}\lambda_5(\tau)d\tau)ds)w(z(t)),\ t \ge t_0, \end{aligned}$$

since $z(t)$ and $w(u)$ are nondecreasing, $u \le w(u)$, and $u(t) \le z(t)$. Therefore, by integrating on $[t_0, t]$, the function z satisfies
(3.4)
$$z(t) \le c+\int_{t_0}^{t}(\lambda_1(s)+\lambda_2(s)\int_{t_0}^{s}(\lambda_3(\tau)+\lambda_4(\tau)\int_{t_0}^{\tau}\lambda_5(r)dr)d\tau)w(z(s)))ds.$$

It follows from Lemma 2.5 that (3.4) yields the estimate (3.3). □

Theorem 3.3. *Let* $a, b, c, k, u, w \in C(\mathbb{R}^+)$, $w(u)$ *be nondecreasing in* u *such that* $u \le w(u)$ *and* $\frac{1}{v}w(u) \le w(\frac{u}{v})$ *for some* $v > 0$. *Suppose that* $f_x(t, 0)$ *is* t_∞*-similar to* $f_x(t, x(t, t_0, x_0))$ *for* $t \ge t_0 \ge 0$ *and* $|x_0| \le \delta$ *for some constant* $\delta > 0$, *the solution* $x = 0$ *of (2.1) is hS with the increasing function* h, *and* g *in (2.2) satisfies*

$$\Big|g(s, y(s))\Big| \le a(s)|y(s)| + b(s)\int_{t_0}^{s}k(\tau)w(|y(\tau)|)d\tau$$

and

$$|h(s, y(s), Ty(s))| \le c(s)w(|y(s)|),$$

where $\int_{t_0}^{\infty} a(s)ds < \infty$, $\int_{t_0}^{\infty} b(s)ds < \infty$, $\int_{t_0}^{\infty} c(s)ds < \infty$, *and* $\int_{t_0}^{\infty} k(s)ds < \infty$. *Then, any solution* $y(t) = y(t, t_0, y_0)$ *of (2.2) is bounded on* $[t_0, \infty)$ *and*

$$|y(t)| \leq h(t)W^{-1}\Big[W(c)+c_2\int_{t_0}^{t}(c(s)+\int_{t_0}^{s}(a(\tau)+b(\tau)\int_{t_0}^{\tau}k(r)dr)d\tau)ds\Big],$$

$t_0 \leq t < b_1$, *where* $c = c_1|y_0|\,h(t_0)^{-1}$, W, W^{-1} *are the same functions as in Lemma 2.5 and*

$$b_1 = \sup\Big\{t \geq t_0 : W(c)+c_2\int_{t_0}^{t}(c(s)+\int_{t_0}^{s}(a(\tau)+b(\tau)\int_{t_0}^{\tau}k(r)dr)d\tau)ds \in \mathrm{domW}^{-1}\Big\}.$$

Proof. Let $x(t) = x(t, t_0, y_0)$ and $y(t) = y(t, t_0, y_0)$ be solutions of (2.1) and (2.2), respectively. By Theorem 2.1, since the solution $x = 0$ of (2.1) is hS, the solution $v = 0$ of (2.3) is hS. Therefore, by Theorem 2.2, the solution $z = 0$ of (2.4) is hS. Applying Lemma 2.3, Lemma 2.4, and the increasing property of the function h, we have

$$\begin{aligned}
|y(t)| &\leq |x(t)| + \int_{t_0}^{t}|\Phi(t,s,y(s))|(\int_{t_0}^{s}|g(\tau,y(\tau))|d\tau + |h(s,y(s),Ty(s))|)ds \\
&\leq c_1|y_0|h(t)\,h(t_0)^{-1} + \int_{t_0}^{t}c_2h(t)h(s)^{-1}\Big(\int_{t_0}^{s}(a(\tau)|y(\tau)| \\
&\quad + b(\tau)\int_{t_0}^{\tau}k(r)w(|y(r)|)dr)d\tau + c(s)w(|y(s)|)\Big)ds \\
&\leq c_1|y_0|h(t)\,h(t_0)^{-1} + \int_{t_0}^{t}c_2h(t)\Big(c(s)w(\frac{|y(s)|}{h(s)}) \\
&\quad + \int_{t_0}^{s}(a(\tau)\frac{|y(\tau)|}{h(\tau)} + b(\tau)\int_{t_0}^{\tau}k(r)w(\frac{|y(r)|}{h(r)})dr)d\tau)\Big)ds.
\end{aligned}$$

Defining $u(t) = |y(t)||h(t)|^{-1}$, then, by Lemma 3.4, we have

$$|y(t)| \leq h(t)W^{-1}\Big[W(c)+c_2\int_{t_0}^{t}(c(s)+\int_{t_0}^{s}(a(\tau)+b(\tau)\int_{t_0}^{\tau}k(r)dr)d\tau)ds\Big],$$

where $c = c_1|y_0|\,h(t_0)^{-1}$. The above estimation yields the desired result since the function h is bounded, and the theorem is proved. □

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