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STABILITY IN NONLINEAR NEUTRAL VOLTERRA DIFFERENCE EQUATIONS

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Abstract. In this paper we use the contraction mapping theorem to obtain asymptotic stability results of the zero solution of the nonlinear neutral Volterra difference equation with variable delays

$$\begin{aligned}\triangle x(n) &= -a(n)\, x(n-\tau_1(n)) + \triangle g(n, x(n-\tau_2(n))) \\ &\quad + \sum_{s=n-\tau_2(n)}^{n-1} k(n,s)\, q(x(s)).\end{aligned}$$

Some conditions which allow the coefficient sequences to change sign and do not ask the boundedness of delays are given. An asymptotic stability theorem with a sufficient condition is proved.

1. Introduction

Certainly, the Lyapunov direct method has been, for more than 100 years, the efficient tool for the study of stability properties of ordinary, functional, partial differential and difference equations. Nevertheless, the application of this method to problems of stability in differential and difference equations with delay has encountered serious difficulties if the delay is unbounded or if the equation has unbounded terms ([3],[4],[6]-[9],[14]). Recently, Burton, Furumochi, Zhang, Raffoul, Islam, Yankson and others have noticed that some of these difficulties vanish or might be overcome by means of fixed point theory (see [1]-[4],[10],[12],[13],[16]-[18]). The fixed point theory does not only solve the problem on stability but has a significant advantage over Lyapunov's direct method. The conditions of the former are often averages but those of the latter are usually pointwise (see [3]).

In this paper we consider the nonlinear neutral Volterra difference equation with variable delays

$$\triangle x(n) = -a(n)\, x(n-\tau_1(n)) + \triangle g(n, x(n-\tau_2(n))) + \sum_{s=n-\tau_2(n)}^{n-1} k(n,s)\, q(x(s)), \tag{1}$$

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with the initial condition

$$x(n) = \psi(n) \text{ for } n \in [m(n_0), n_0] \cap \mathbb{Z},$$

where ψ is bounded sequence and for each $n_0 \in \mathbb{Z}^+$,

$$m_j(n_0) = \inf\{n - \tau_j(n),\ n \geq n_0\},\ m(n_0) = \min\{m_j(n_0),\ j = 1, 2\}.$$

Here $\triangle$ denotes the forward difference operator $\triangle x(t) = x(n+1) - x(n)$ for any sequence $\{x(n),\ n \in \mathbb{Z}^+\}$. Throughout this paper we assume that $a : \mathbb{Z}^+ \to \mathbb{R}$, $k : \mathbb{Z}^+ \times ([m_2(n_0), \infty) \cap \mathbb{Z}) \to \mathbb{R}$, $q : \mathbb{R} \to \mathbb{R}$ and $\tau_1, \tau_2 : \mathbb{Z}^+ \to \mathbb{Z}^+$ with $n - \tau_1(n) \to \infty$ and $n - \tau_2(n) \to \infty$ as $n \to \infty$. The functions $g(n, x)$ and $q(x)$ are locally Lipschitz in x. That is, there are positive constants E and L so that if $|x|, |y| \leq L_1$ for some positive constant L_1 then

$$|g(n, x) - g(n, y)| \leq E\|x - y\| \text{ and } g(n, 0) = 0, \tag{2}$$

and

$$|q(x) - q(y)| \leq L\|x - y\| \text{ and } q(0) = 0. \tag{3}$$

Equation (1) and its special cases have been investigated by many authors. For example, Raffoul in [12] and Yankson in [16] have studied the equation

$$\triangle x(n) = -a(n)\, x(n - \tau_1(n)), \tag{4}$$

and proved the following.

Theorem A (Raffoul [12]). *Suppose that $\tau_1(n) = r$ and $a(n + r) \neq 1$ and there exists a constant $\alpha < 1$ such that*

$$\sum_{s=n-r}^{n-1} |a(s+r)| + \sum_{s=0}^{n-1} \left(|a(s+r)| \left| \prod_{k=s+1}^{n-1} [1 - a(k+r)] \right| \sum_{u=s-r}^{s-1} |a(u+r)| \right) \leq \alpha, \tag{5}$$

for all $n \in \mathbb{Z}^+$ and $\prod_{s=0}^{n-1} [1 - a(s+r)] \to 0$ as $n \to \infty$. Then, for every small initial sequence $\psi : [-r, 0] \cap \mathbb{Z} \to \mathbb{R}$, the *solution $x(n) = x(n, 0, \psi)$ of (4) is bounded and tends to zero as $n \to \infty$.*

Theorem B (Yankson [16]). *Suppose that the inverse sequence g of $n - \tau_1(n)$ exists, $1 - a(g(n)) \neq 0$ and there exists a constant $\alpha \in (0, 1)$ for all $n \in [n_0, \infty) \cap \mathbb{Z}$ such that*

$$\sum_{s=n-\tau_1(n)}^{n-1} |a(g(s))| + \sum_{s=n_0}^{n-1} \left(|a(g(s))| \left| \prod_{k=s+1}^{n-1} [1 - a(g(s))] \right| \sum_{u=s-\tau_1(s)}^{s-1} |a(g(s))| \right) \leq \alpha. \tag{6}$$

Then the zero solution of (4) is asymptotically stable if $\prod_{s=n_0}^{n-1} [1 - a(g(s))] \to 0$ as $n \to \infty$.

Obviously, Theorem B improves and generalizes Theorem A.

Our purpose here is to give, by using the contraction mapping principle, asymptotic stability results of a nonlinear neutral Volterra difference equation with variable delays (1). For details on contraction mapping principle we refer the reader to [15] and for more on the calculus of difference equations, we refer the reader to [5] and [11]. It is important to note that, in our consideration, the neutral term $\triangle g(n, x(n - \tau_2(n)))$ of (1) produces nonlinearity in the neutral term

$\triangle x(n-\tau_2(n))$. While, the neutral term $\triangle x(n-\tau_2(n))$ in [1, 17] enters linearly. As a consequence, we have performed an appropriate analysis which is different from that used in [1, 17] to construct the mapping in order to employ fixed point theorems. Also, the results presented in this paper improve and generalize the main results in [12, 16].

2. Main results

Let $D(n_0)$ denote the set of bounded sequences $\psi : [m(n_0), n_0] \cap \mathbb{Z} \to \mathbb{R}$ with the maximum norm $\|.\|$. Also, let $(\mathbb{B}, \|.\|)$ be the Banach space of bounded sequences $x : [m(n_0), \infty) \cap \mathbb{Z} \to \mathbb{R}$ with the maximum norm. For each $(n_0, \psi) \in \mathbb{Z}^+ \times D(n_0)$, a solution of (1) through (n_0, ψ) is a sequence $[m(n_0), n_0 + \alpha] \cap \mathbb{Z} \to \mathbb{R}$ for some positive constant $\alpha > 0$ such that x satisfies (1) on $[n_0, n_0 + \alpha) \cap \mathbb{Z}$ and $x = \psi$ on $[m(n_0), n_0] \cap \mathbb{Z}$. We denote such a solution by $x(n) = x(n, n_0, \psi)$. For each $(n_0, \psi) \in \mathbb{Z}^+ \times D(n_0)$, there exists a unique solution $x(n) = x(n, n_0, \psi)$ of (1) defined on $[m(n_0), \infty) \cap \mathbb{Z}$. For a fixed n_0, we define $\|\psi\| = \{|\psi(n)| : n \in [m(n_0), n_0] \cap \mathbb{Z}\}$.

Let $h_j : [m(n_0), \infty) \cap \mathbb{Z} \to \mathbb{R}$ be an arbitrary sequence. Rewrite (1) as

$$\begin{aligned}\triangle x(n) = &-\sum_{j=1}^{2} h_j(n)\, x(n) + \triangle_n \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} h_j(s)\, x(s) \\ &+ \sum_{j=1}^{2} h_j(n-\tau_j(n))\, x(n-\tau_j(n)) \\ &- a(n)\, x(n-\tau_1(n)) + \triangle g(n, x(n-\tau_2(n))) \\ &+ \sum_{s=n-\tau_2(n)}^{n-1} k(n,s)\, q(x(s)), \end{aligned} \tag{7}$$

where $\triangle_n$ represents that the difference is with respect to n. If we let $H(n) = 1 - \sum_{j=1}^{2} h_j(n)$ then (7) is equivalent to

$$\begin{aligned}x(n+1) = &\, H(n)\, x(n) + \triangle_n \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} h_j(s)\, x(s) \\ &+ \sum_{j=1}^{2} h_j(n-\tau_j(n))\, x(n-\tau_j(n)) \\ &- a(n)\, x(n-\tau_1(n)) + \triangle g(n, x(n-\tau_2(n))) \\ &+ \sum_{s=n-\tau_2(n)}^{n-1} k(n,s)\, q(x(s)). \end{aligned} \tag{8}$$

Lemma 2.1. *Suppose that $H(n) \neq 0$ for all $n \in [n_0, \infty) \cap \mathbb{Z}$. Then x is a solution of equation (1) if and only if*

$$\begin{aligned}
x(n) &= \left\{ x(n_0) - g(n_0, x(n_0 - \tau_2(n_0))) - \sum_{j=1}^{2} \sum_{s=n_0-\tau_j(n_0)}^{n_0-1} h_j(s)\, x(s) \right\} \prod_{u=n_0}^{n-1} H(u) \\
&\quad + g(n, x(n - \tau_2(n))) + \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} h_j(s)\, x(s) \\
&\quad + \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \{ [h_1(s - \tau_1(s)) - a(s)]\, x(s - \tau_1(s)) \\
&\quad + h_2(s - \tau_2(s))\, x(s - \tau_2(s)) + \sum_{u=s-\tau_2(s)}^{s-1} k(s,u)\, q(x(u)) \Bigg\} \\
&\quad - \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \{1 - H(s)\} \prod_{u=s+1}^{n-1} H(u) \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u) \\
&\quad - \sum_{s=n_0}^{n-1} \{1 - H(s)\} \prod_{u=s+1}^{n-1} H(u)\, g(s, x(s - \tau_2(s))). \qquad (9)
\end{aligned}$$

Proof. Let x be a solution of (1). By multiplying both sides of (8) by $\prod_{u=n_0}^{n} H^{-1}(u)$ and by summing from n_0 to $n-1$ we obtain

$$\begin{aligned}
&\sum_{s=n_0}^{n-1} \triangle \left[\prod_{u=n_0}^{s-1} H^{-1}(u)\, x(s) \right] \\
&= \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u)\, \triangle_s \sum_{j=1}^{2} \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u) \\
&\quad + \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \sum_{j=1}^{2} \{ h_j(s - \tau_j(s)) \}\, x(s - \tau_j(s)) \\
&\quad + \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \left\{ -a(s)\, x(s - \tau_1(s)) + \sum_{u=s-\tau_2(s)}^{s-1} k(s,u)\, q(x(u)) \right\} \\
&\quad + \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u)\, \triangle g(s, x(s - \tau_2(s))).
\end{aligned}$$

As a consequence, we arrive at

$$
\begin{aligned}
&\prod_{u=n_0}^{n-1} H^{-1}(u)\, x(n) - \prod_{u=n_0}^{n_0-1} H^{-1}(u)\, x(n_0) \\
&= \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \triangle_s \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u) \\
&+ \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \left\{h_j(s-\tau_j(s))\right\} x(s-\tau_j(s)) \\
&+ \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \left\{ -a(s)\, x(s-\tau_1(s)) + \sum_{u=s-\tau_2(s)}^{s-1} k(s,u)\, q(x(u)) \right\} \\
&+ \sum_{s=n_0}^{n-1} \prod_{u=n_0}^{s} H^{-1}(u) \triangle g(s, x(s-\tau_2(s))).
\end{aligned}
$$

By dividing both sides of the above expression by $\prod_{u=n_0}^{n-1} H^{-1}(u)$ we get

$$
\begin{aligned}
x(n) &= x(n_0) \prod_{u=n_0}^{n-1} H(u) \\
&+ \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \triangle_s \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u) \\
&+ \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \left\{h_j(s-\tau_j(s))\right\} x(s-\tau_j(s)) \\
&+ \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \left\{ -a(s)\, x(s-\tau_1(s)) + \sum_{u=s-\tau_2(s)}^{s-1} k(s,u)\, q(x(u)) \right\} \\
&+ \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \triangle g(s, x(s-\tau_2(s))).
\end{aligned}
\tag{10}
$$

By performing a summation by parts, we have

$$
\begin{aligned}
&\sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \triangle_s \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u) \\
&= \sum_{s=n-\tau_j(n)}^{n-1} h_j(s)\, x(s) - \prod_{u=n_0}^{n-1} H(u) \sum_{s=n_0-\tau_j(n_0)}^{n_0-1} h_j(s)\, x(s) \\
&- \sum_{s=n_0}^{n-1} \left\{1 - H(s)\right\} \prod_{u=s+1}^{n-1} H(u) \sum_{u=s-\tau_j(s)}^{s-1} h_j(u)\, x(u),
\end{aligned}
\tag{11}
$$

and

$$
\begin{aligned}
&\sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \triangle g(s, x(s-\tau_2(s))) \\
&= -g(n_0, x(n_0-\tau_2(n_0))) \prod_{u=n_0}^{n-1} H(u) + g(n, x(n-\tau_2(n))) \\
&- \sum_{s=n_0}^{n-1} \{1-H(s)\} \prod_{u=s+1}^{n-1} H(u) g(s, x(s-\tau_2(s))). \qquad (12)
\end{aligned}
$$

Finally, substituting (11) and (12) into (10) completes the proof. □

Definition 2.2. The zero solution of (1) is Lyapunov stable if for any $\epsilon > 0$ and any integer $n_0 \geq 0$ there exists a $\delta > 0$ such that $|\psi(n)| \leq \delta$ for $n \in [m(n_0), n_0] \cap \mathbb{Z}$ implies $|x(n, n_0, \psi)| \leq \epsilon$ for $n \in [n_0, \infty) \cap \mathbb{Z}$.

Theorem 2.3. *Let $H(n) \neq 0$ for all $n \in [n_0, \infty) \cap \mathbb{Z}$. Suppose that (2) and (3) holds, and there exists a positive constant M and a constant $\alpha \in (0,1)$ such that for $n \in [n_0, \infty) \cap \mathbb{Z}$,*

$$\left| \prod_{u=n_0}^{n-1} H(u) \right| \leq M, \qquad (13)$$

and

$$
\begin{aligned}
&E + \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} |h_j(s)| \\
&+ \sum_{s=n_0}^{n-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \{ |h_1(s-\tau_1(s)) - a(s)| \\
&+ |h_2(s-\tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \bigg\} \\
&+ \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} |1-H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \sum_{u=s-\tau_j(s)}^{s-1} |h_j(u)| \\
&+ E \sum_{s=n_0}^{n-1} |1-H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \leq \alpha . \qquad (14)
\end{aligned}
$$

Then the zero solution of (1) is stable.

Proof. Let $\epsilon > 0$ be given. Choose $\delta > 0$ such that

$$(M + \alpha M)\delta + \alpha\epsilon \leq \epsilon.$$

Let $\psi \in D(n_0)$ such that $|\psi(n)| \leq \delta$ for $n \in [m(n_0), n_0] \cap \mathbb{Z}$. Define

$$\mathbb{S} = \{\varphi \in \mathbb{B} : \varphi(n) = \psi(n) \text{ for } n \in [m(n_0), n_0] \cap \mathbb{Z},\ \|\varphi\| \leq \epsilon\}.$$

This $(\mathbb{S}, \|.\|)$ is a complete metric space where $\|.\|$ is the maximum norm.

Use (9) to define the operator $P:\mathbb{S}\rightarrow\mathbb{S}$ by $(P\varphi)(n)=\psi(n)$ for $n\in[m(n_0),n_0]\cap\mathbb{Z}$ and

$$\begin{aligned}
&(P\varphi)(n)\\
&=\left\{\psi(n_0)-g(n_0,\psi(n_0-\tau_2(n_0)))-\sum_{j=1}^{2}\sum_{s=n_0-\tau_j(n_0)}^{n_0-1}h_j(s)\psi(s)\right\}\prod_{u=n_0}^{n-1}H(u)\\
&+g(n,\varphi(n-\tau_2(n)))+\sum_{j=1}^{2}\sum_{s=n-\tau_j(n)}^{n-1}h_j(s)\varphi(s)\\
&+\sum_{s=n_0}^{n-1}\prod_{u=s+1}^{n-1}H(u)\{[h_1(s-\tau_1(s))-a(s)]\varphi(s-\tau_1(s))\\
&+h_2(s-\tau_2(s))\varphi(s-\tau_2(s))+\sum_{u=s-\tau_2(s)}^{s-1}k(s,u)q(\varphi(u))\right\}\\
&-\sum_{j=1}^{2}\sum_{s=n_0}^{n-1}\{1-H(s)\}\prod_{u=s+1}^{n-1}H(u)\sum_{u=s-\tau_j(s)}^{s-1}h_j(u)\varphi(u)\\
&-\sum_{s=n_0}^{n-1}\{1-H(s)\}\prod_{u=s+1}^{n-1}H(u)g(s,\varphi(s-\tau_2(s))), \qquad (15)
\end{aligned}$$

for $n\in[n_0,\infty)\cap\mathbb{Z}$. Clearly, $P\varphi$ is bounded. We first show that P maps from $\mathbb{S}$ to $\mathbb{S}$. We have

$$\begin{aligned}
&|(P\varphi)(n)|\\
&\leq M\delta+\alpha M\delta+\left\{E+\sum_{j=1}^{2}\sum_{s=n-\tau_j(n)}^{n-1}|h_j(s)|\right.\\
&+\sum_{s=n_0}^{n-1}\left|\prod_{u=s+1}^{n-1}H(u)\right|\{|h_1(s-\tau_1(s))-a(s)|\\
&+|h_2(s-\tau_2(s))|+L\sum_{u=s-\tau_2(s)}^{s-1}|k(s,u)|\right\}\\
&+\sum_{j=1}^{2}\sum_{s=n_0}^{n-1}|1-H(s)|\left|\prod_{u=s+1}^{n-1}H(u)\right|\sum_{u=s-\tau_j(s)}^{s-1}|h_j(u)|\\
&+E\sum_{s=n_0}^{n-1}|1-H(s)|\left|\prod_{u=s+1}^{n-1}H(u)\right|\Bigg\}\|\varphi\|\\
&\leq(M+\alpha M)\delta+\alpha\epsilon\\
&\leq\epsilon,
\end{aligned}$$

by (2), (3), (13) and (14). Thus P maps $\mathbb{S}$ into itself. We next show that P is a contraction. Let $\varphi_1, \varphi_2 \in \mathbb{S}$, then

$$\begin{aligned}
&\left|(P\varphi_1)(n) - (P\varphi_2)(n)\right| \\
&\leq \Bigg\{ E + \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} |h_j(s)| \\
&+ \sum_{s=n_0}^{n-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \Big\{ |h_1(s-\tau_1(s)) - a(s)| \\
&+ |h_2(s-\tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \Big\} \\
&+ \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} |1-H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \sum_{u=s-\tau_j(s)}^{s-1} |h_j(u)| \\
&+ E \sum_{s=n_0}^{n-1} |1-H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \Bigg\} \|\varphi_1 - \varphi_2\| \\
&\leq \alpha \|\varphi_1 - \varphi_2\|,
\end{aligned}$$

by (2), (3) and (14). This shows that P is a contraction with contraction constant α. Thus, by the contraction mapping principle ([15], p. 2), P has a unique fixed point x in $\mathbb{S}$ which is a solution of (1) with $x = \psi$ on $[m(n_0), n_0] \cap \mathbb{Z}$ and $|x(n)| = |x(n, n_0, \psi)| \leq \epsilon$ for $n \in [n_0, \infty) \cap \mathbb{Z}$. This proves that the zero solution of (1) is stable. □

Definition 2.4. The zero solution of (1) is asymptotically stable if it is Lyapunov stable and if for any integer $n_0 \geq 0$ there exists a $\delta > 0$ such that $|\psi(n)| \leq \delta$ for $n \in [m(n_0), n_0] \cap \mathbb{Z}$ implies $x(n, n_0, \psi) \to 0$ as $n \to \infty$.

Theorem 2.5. *Assume that the hypotheses of Theorem 2.3 hold. Also assume that*

$$\prod_{u=n_0}^{n-1} H(u) \to 0 \ \text{as} \ n \to \infty. \tag{16}$$

Then the zero solution of (1) is asymptotically stable.

Proof. We have already proved that the zero solution of (1) is stable. Let $\psi \in D(n_0)$ such that $|\psi(n)| \leq \delta$ for $n \in [m(n_0), n_0] \cap \mathbb{Z}$ and define

$$\begin{aligned}
\mathbb{S}^* = \{&\varphi \in \mathbb{B} : \varphi(n) = \psi(n) \ \text{for} \ n \in [m(n_0), n_0] \cap \mathbb{Z}, \ \|\varphi\| \leq \epsilon \\
&\text{and} \ \varphi(n) \to 0 \ \text{as} \ n \to \infty\}.
\end{aligned}$$

Define $P : \mathbb{S}^* \to \mathbb{S}^*$ by (15). From the proof of Theorem 2.3, the map P is a contraction with the contraction constant α and for every $\varphi \in \mathbb{S}^*$, $\|P\varphi\| \leq \epsilon$.

We next show that $(P\varphi)(n) \to 0$ as $n \to \infty$. There are five terms on the right hand side in (15). Denote them, respectively, by I_k, $k = 1, 2, ..., 6$. It is obvious that the first term I_1 tends to zero as $t \to \infty$, by condition (16). Also, due to the condition (2) and the facts that $\varphi(n) \to 0$ and $n - \tau_j(n) \to \infty$ for $j = 1, 2$ as $n \to \infty$, the second term I_2 tends to zero, as $n \to \infty$. Left to show that each one of the remaining terms in (15), go to zero at infinity.

Let $\varphi \in \mathbb{S}^*$ be fixed. For the given $\epsilon_1 > 0$, we choose $N_0 > n_0$ large enough such that $n - \tau_j(n) \geq N_0$, $j = 1, 2$ implies $|\varphi(s)| < \epsilon_1$ if $s \geq n - \tau_j(n)$. Therefore, the third term I_3 in (15) satisfies

$$\begin{aligned}
|I_3| &= \left| \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} h_j(s)\,\varphi(s) \right| \\
&\leq \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} |h_j(s)|\,|\varphi(s)| \\
&\leq \epsilon_1 \sum_{j=1}^{2} \sum_{s=n-\tau_j(n)}^{n-1} |h_j(s)| \leq \alpha\epsilon_1 < \epsilon_1.
\end{aligned}$$

Thus, $I_3 \to 0$ as $n \to \infty$. Now for a given $\epsilon_1 > 0$, there exists a $N_1 > n_0$ such that $s \geq N_1$ implies $|\varphi(s - \tau_j(s))| < \epsilon_1$ for $j = 1, 2$. Thus, for $n \geq N_1$, the term I_4 in (15) satisfies

$$\begin{aligned}
|I_4| = &\left| \sum_{s=n_0}^{n-1} \prod_{u=s+1}^{n-1} H(u) \left\{ [h_1(s - \tau_1(s)) - a(s)]\,\varphi(s - \tau_1(s)) \right. \right. \\
&\left. \left. + [h_2(s - \tau_2(s)) - \phi(s)]\,\varphi(s - \tau_2(s)) + \sum_{u=s-\tau_2(s)}^{s-1} k(s,u)\,q(\varphi(u)) \right\} \right| \\
&\leq \sum_{s=n_0}^{N_1-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \left\{ |h_1(s - \tau_1(s)) - a(s)|\,|\varphi(s - \tau_1(s))| \right. \\
&\left. + |h_2(s - \tau_2(s)) - \phi(s)|\,|\varphi(s - \tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)|\,|\varphi(u)| \right\} \\
&+ \sum_{s=N_1}^{n-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \left\{ |h_1(s - \tau_1(s)) - a(s)|\,|\varphi(s - \tau_1(s))| \right. \\
&\left. + |h_2(s - \tau_2(s))|\,|\varphi(s - \tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)|\,|\varphi(u)| \right\} \\
&\leq \sup_{\sigma \geq m(n_0)} |\varphi(\sigma)| \sum_{s=n_0}^{N_1-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \left\{ |h_1(s - \tau_1(s)) - a(s)| \right. \\
&\left. + |h_2(s - \tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \right\} \\
&+ \epsilon_1 \sum_{s=N_1}^{n-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \left\{ |h_1(s - \tau_1(s)) - a(s)| \right. \\
&\left. + |h_2(s - \tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \right\}.
\end{aligned}$$

By (16), we can find $N_2 > N_1$ such that $n \geq N_2$ implies

$$\begin{aligned}
&\sup_{\sigma \geq m(n_0)} |\varphi(\sigma)| \sum_{s=n_0}^{N_1-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \Big\{ |h_1(s-\tau_1(s)) - a(s)| \\
&+ |h_2(s-\tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \Big\} \\
&= \sup_{\sigma \geq m(n_0)} |\varphi(\sigma)| \left| \prod_{u=N_2}^{n-1} H(u) \right| \sum_{s=n_0}^{N_1-1} \left| \prod_{u=s+1}^{N_2-1} H(u) \right| \Big\{ |h_1(s-\tau_1(s)) - a(s)| \\
&+ |h_2(s-\tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \Big\} < \epsilon_1 .
\end{aligned}$$

Now, apply (14) to have $|I_4| < \epsilon_1 + \alpha\epsilon_1 < 2\epsilon_1$. Thus, $I_4 \to 0$ as $n \to \infty$. Similarly, by using (14), then, if $n \geq N_2$ then term I_5 and I_6 in (15) satisfy

$$\begin{aligned}
|I_5| &= \left| \sum_{j=1}^{2} \sum_{s=n_0}^{n-1} \{1 - H(s)\} \prod_{u=s+1}^{n-1} H(u) \sum_{u=s-\tau_j(s)}^{s-1} h_j(u) \varphi(u) \right| \\
&\leq \sup_{\sigma \geq m(n_0)} |\varphi(\sigma)| \left| \prod_{u=N_2}^{n-1} H(u) \right| \sum_{j=1}^{2} \sum_{s=n_0}^{N_1-1} |1 - H(s)| \left| \prod_{u=s+1}^{N_2-1} H(u) \right| \sum_{u=s-\tau_j(s)}^{s-1} |h_j(u)| \\
&+ \epsilon_1 \sum_{j=1}^{2} \sum_{s=N_1}^{n-1} |1 - H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \sum_{u=s-\tau_j(s)}^{s-1} |h_j(u)| \\
&< \epsilon_1 + \alpha\epsilon_1 < 2\epsilon_1,
\end{aligned}$$

and

$$\begin{aligned}
|I_6| &= \left| \sum_{s=n_0}^{n-1} \{1 - H(s)\} \prod_{u=s+1}^{n-1} H(u) g(s, \varphi(s-\tau_2(s))) \right| \\
&\leq \sup_{\sigma \geq m(n_0)} |\varphi(\sigma)| E \left| \prod_{u=N_2}^{n-1} H(u) \right| \sum_{s=n_0}^{N_1-1} |1 - H(s)| \left| \prod_{u=s+1}^{N_2-1} H(u) \right| \\
&+ \epsilon_1 E \sum_{s=N_1}^{n-1} |1 - H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \\
&< \epsilon_1 + \alpha\epsilon_1 < 2\epsilon_1.
\end{aligned}$$

Thus, $I_5, I_6 \to 0$ as $n \to \infty$. In conclusion $(P\varphi)(n) \to 0$ as $n \to \infty$, as required. Hence P maps $\mathbb{S}^*$ into $\mathbb{S}^*$.

By the contraction mapping principle, P has a unique fixed point $x \in \mathbb{S}^*$ which solves (1). Therefore, the zero solution of (1) is asymptotically stable. □

Letting $\tau_1 = 0$, we have

Corollary 2.6. *Let $H(n) \neq 0$ for all $n \in [n_0, \infty) \cap \mathbb{Z}$. Suppose that (2) and (3) hold and there exists a constant $\alpha \in (0,1)$ such that for $n \in [n_0, \infty) \cap \mathbb{Z}$,*

$$\begin{aligned} & E + \sum_{s=n-\tau_2(n)}^{n-1} |h_2(s)| \\ & + \sum_{s=n_0}^{n-1} \left| \prod_{u=s+1}^{n-1} H(u) \right| \left(|h_1(s) - a(s)| + |h_2(s - \tau_2(s))| + L \sum_{u=s-\tau_2(s)}^{s-1} |k(s,u)| \right) \\ & + \sum_{s=n_0}^{n-1} |1 - H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \sum_{u=s-\tau_2(s)}^{s-1} |h_2(u)| \\ & + E \sum_{s=n_0}^{n-1} |1 - H(s)| \left| \prod_{u=s+1}^{n-1} H(u) \right| \leq \alpha \ . \end{aligned} \tag{17}$$

Then the zero solution of (1) is asymptotically stable if

$$\prod_{u=n_0}^{n-1} H(u) \to 0 \text{ as } n \to \infty.$$

For the special case $g(n,x) = 0$ and $q(x) = 0$, we can get

Corollary 2.7. *Suppose that $1 - h_1(n) \neq 0$ for all $n \in [n_0, \infty) \cap \mathbb{Z}$, and there exists a constant $\alpha \in (0,1)$ such that for $n \in [n_0, \infty) \cap \mathbb{Z}$,*

$$\begin{aligned} & \sum_{s=n-\tau_1(n)}^{n-1} |h_1(s)| + \sum_{s=n_0}^{n-1} \left| \prod_{u=s+1}^{n-1} [1 - h_1(n)] \right| |h_1(s - \tau_1(s)) - a(s)| \\ & + \sum_{s=n_0}^{n-1} |h_1(s)| \left| \prod_{u=s+1}^{n-1} [1 - h_1(n)] \right| \sum_{u=s-\tau_1(s)}^{s-1} |h_1(u)| \leq \alpha \ . \end{aligned} \tag{18}$$

Then the zero solution of (4) is asymptotically stable if

$$\prod_{u=n_0}^{n-1} [1 - h_1(n)] \to 0 \text{ as } n \to \infty.$$

Remark 2.8. When $h_1(s) = a(g(s))$, Corollary 2.7 reduces to Theorem B.

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