RESULTS ON UNIQUENESS OF PERIODIC SOLUTION, EXPONENTIAL STABILITY AND CONTROLLABILITY PROPERTIES OF NEUTRAL DELAY SYSTEM

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Abstract

The variation of constant method is employed to evaluate the periodic solution of a linear neutral system with an input function. Uniqueness of the obtained solution is estabilished and proved by utilizing inversion theory on a perturbed differential operator. The exponential stability of the system equation and the computation of the maximum delay bound for the system to be asymptotically stable are analyzed using the resolvent matrix of the system equation. The controllability of the system is study by the analyses of the linear ordinary control and the free control parts of the linear neutral system for: properness, non-singularity of the gramian matrix, canonical form of the controllable matrix and the non zero/pole cancellation of the transfer function matrix. Results obtained are employed on neutral delay model of a partial element equivalent circuit (PEEC) consisting of a retarded mutual coupling between the partial inductance to confirm the suitablility of the test.

Keywords: *uniqueness, stability, controllability, resolvent matrix.*

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1.1 Introduction

The qualitative properties of differential equation models in system theory are greatly improved by the introduction of the delay (neutral) differential equation. This is because the point-wise (instantaneous) reaction of the system for any perturbation is addressed. This important attribute has endeared the application of the neutral differential equation in the formulation of mathematical models in many field of engineering and sciences (see: [2, 3, 7, 8]).

Neutral differential equation is a delay equation with time lag $r(t) : E \to E, r(t) > 0$ incorporated in both the derivative and the state of the system. This time lag accounts for the non-instantaneous reaction of the system for any action. A general non homogeneous neutral differential equation is defined as

$$\frac{d''}{dt''}\rho(x(t), x(t-r)) = g(x(t)) + \eta(u(t)), n = 1, 2, \ldots \tag{1.0}$$

where $g(x(t)), \eta(u(t))$ are the state and the input function of the system respectively.

The analysis of equation (1.0) begins with the establishment of the conditions for the existence and uniqueness of the system solution, which in most cases provides the methodological basis for computing the system solution. Many mathematical concepts have been used by researchers to achieve this aim (see: [4, 7, 10, 18]). But in all the methods employed, the general idea is the establishment of boundeness and continuity of the functional in the space of its operation. The establishments of the uniqueness of the system solution also guaranties the analysis of the qualitative behaviour of the solution for any perturbation of the system equations, such as; asymptotic stability, controllability and observability. But these analyses are not easily come by, due to the transcendental character of the system equation. Considerable literature devoted to the study of the asymptotic and exponential stability behaviour of solution of equation (1.0) abounds in ([7, 8, 10, 12, 13, 14]). Also, researches on the controllability are found in the works of ([1, 2, 16]).

The aim of this research work is to obtain a periodic solution of the linear neutral system of equation (1.0), with constant delay ($r > 0$) and an initial value $x(t_0) = \varphi_0$ by employing the variation of constant method. The inversion concept of a perturbed differential operator which yields the sum of a contraction and a compact map by Burton [4] is used as a tool in establishing the uniqueness of the periodic solution of the system. The exponential stability of the system equation is established by the analysis of the system resolvent matrix which must be negative definite. The resolvent matrix is also utilized to approximate the maximum delay bound for the system to be

asymptotically stable. The controllability of the system is study by the analyses of the linear ordinary control and the free control parts of system equation for; properness, non-singularity of the gramian matrix, canonical form of the controllable matrix and the non zero/pole cancellation of the transfer function matrix. Application of obtained results are employed on neutral delay model of a partial element equivalent circuit (PEEC) consisting of a retarded mutual coupling between the partial inductance which confirm the suitablility of the test.

2.1 Preliminary Results

Let $U \subset B_H([t-r,t],E), E \subset R^n$ where B_H is the Banach Space of continuous functions and $f \subset C_T^1(U)$, such that $f : E \times U \to R^n$ is a continuous mapping which is T-periodic in E and compact in U, then a first order time inveriant neutral delay equation is defined as

$$\dot{x}(t) + \dot{x}(t-r) = f(t, Ax(t) + Du(t)), \tag{2.0}$$

where A and D are $n \times n$ and $n \times 1$ matrices respectively, and $r > 0$ is the time lag. The T-periodic solution is a vector function $x : [t-r,t] \to E$, which is dependence on the time *lag* $r > 0$ and the $T-$period in E such that

$$x(t+T) = x(t) \quad and \quad f_{t+T} = f_t.$$

Consider the initial value linear system of (2.0) in the form

$$\begin{aligned} &\tfrac{d}{dt}(x(t) - x(t-r)) = Ax(t) + Du(t) \\ &x(t_0) = x_0, \end{aligned} \tag{2.1}$$

with an output function $y(t) = Cx(t)$. By variation of constant method, (2.1) is expressed as

$$\int_{t-r}^{t} \dot{x}(\tau)e^{-A\tau}d\tau = x_0 + \int_{t_0}^{t} Du(\tau)e^{-A\tau}d\tau. \tag{2.2}$$

Since the solution vector function $x : [t-r,t] \to E$ is T-periodic, then (2.2) is equivalent to

$$\int_{t-T}^{t} \dot{x}(\tau)e^{-A\tau}d\tau = x_0 + \int_{t-r}^{t-T} x(\tau)e^{-A\tau}d\tau + \int_{t_0}^{t} Du(\tau)e^{-A\tau}d\tau.$$

Integrating by part the term on the left and second term on the right yield

$x(t)e^{-At} - x(t-T)e^{-A(t-T)} + A\int_{t-T}^{t} x(\tau)e^{-A\tau}d\tau =$

$$x_0 - x(t-T)e^{-A(t-T)} - x(t-r)e^{-A(t-r)} + A\int_{t-T}^{t} x(\tau)e^{-A\tau}d\tau + \int_{t_0}^{t} Du(\tau)e^{A\tau}d\tau$$

$$x(t) = x_0e^{At} + x(t-r)e^{-A(t-r)} + A\left[\int_{t-T}^{t} x(\tau)e^{-A(t-\tau)}d\tau + \int_{t-r}^{t-T} x(\tau)e^{-A(t-\tau)}d\tau\right] + \int_{t_0}^{t} Du(\tau)e^{-A(t-\tau)}d\tau.$$

Re-arranging the above equation, the integral solution

$$x(t) = x_0e^{at} + x(t-r)e^{-A(t-r)} + A\int_{t-r}^{t} x(\tau)e^{-A(t-\tau)}d\tau + \int_{t_0}^{t} Du(\tau)e^{-A(t-\tau)}d\tau. \tag{2.3}$$

is obtained.

3.1 Uniqueness of Solution (2.3)

The development of theory on uniqueness of solution (2.3) is enhance by the utilization of some known results on the behaviour of f on B_H stated as follows:

3.1.1 The Krasnoselskii Hypothesis

Krasnoselskii[11], states that the inversion of a perturbed differential operator yields the sum of a contraction and a compact map. This hypothesis is essential tool in the analysis of existence and uniqueness of solutions of the differential equations as shown in [15], [17]. The theorem combines the Banach contraction mapping principle and the Schauder fixed point theorem to establish bound conditions and convergent point in the non-empty closed convex subset of B_H. Burton [4] presents a modified form of the Krasnoselskii hypothesis as follows;

Theorem 3.1

Let $X \subset B_H$ be a close convex non empty subset, assume that Q and R map X into B_H such that $Q, R : X \to X$, then

(i) for $x_0, x_2, \in X, Qx_1 + Rx_2 \in X$

(ii) R is a contraction with contraction constant $0 \leq k < 1$,

(iii) Q is continuous with $Q(X)$ contained in a compact set,

then there exists a unique $x \in X$ such that $Qx_1 + Rx_2 = x$.

3.1 Definitions 3.1

1. (X, ℓ) be a metric space and $R : X \to X$. R is a contraction on X such that for $\varphi, \phi \in X$ and $\varphi \neq \phi$, then $\ell(R\varphi, R\phi) < \ell(\varphi, \phi)$ and for all $\varepsilon > 0$, there exist $0 \leq k < 1$ such that $\varphi, \phi \in X, \ell(\varphi, \phi) \geq \varepsilon$ implies that $\ell(R\varphi, R\phi) \leq k\ell f(\varphi, \phi)$

2. $X \subset B_H$ is a convex non empty subset with $\varphi, \phi \in X$, then X is a closed segment with boundary points φ, ϕ such that $\vartheta = \{v = k\varphi + (1-k)\phi;\ 0 \leq k \leq 1\}$.

3. $X \subset B_H$ be a closed convex non empty subset and $\alpha : X \to X$ is a compact set in X if $\varphi(t) \in X$ there exist subsequence $\varphi(t_n)$, such that $[\alpha\varphi]_{i=0}^{n}$ converges in X

Mean Value Theorem

Theorem 3.1.2

Driver [9], states that if $f(x)$ is continuous and differentiable on the interval $[a, b]$, then there exists at least a number $c \in [a, b]$ such that

$$f(b) - f(a) = f'(c)(b - a). \tag{3.0}$$

3.2 Main Result

Theorem 3.3

Consider the general form of system (2.1) in the form of (1.0) as

$$\frac{d}{dt}\rho(x(t), x(t-r)) = f(x(t), u(t)), \tag{3.1}$$

where $f(x(t), u(t), t) = g(x(t)) + \eta(u(t))$ is continuous and differential on $\Gamma = [t_0 - \alpha \leq t \leq t_0 + \alpha, \varphi(t_0) - \beta \leq \varphi \leq \varphi(t_0) + \beta]$, Lipschitzian in the t variable, and for constants
$k_1, k_2 > 0, \|g(x(t))\| \leq k_1, \|\eta(u(t))\| \leq k_2$, then for any continuous initial value $\varphi : [t - h, t] \to E$ there exists a compact continuous periodic function $f_t(\varphi(t)) \in X \subset B_H$ which maps X to itself so that

$$f_T(\varphi(t)) = \varphi_0 e^{At} + \varphi_t(t)e^{-A(t-r)} + A\int_{t-r}^{t} g_T(\varphi(\tau)e^{-A(t-\tau)})d\tau + \int_{t_0}^{t} \eta_T(u(\tau)e^{-A(t-\tau)})d\tau,$$

defined the unique T-periodic solution of (3.1)

Proof

The hypotheses of the theorem are proved in steps as follows:

Step (i); showing that $f(x(t), u(t), t)$ is Lipschitzian.

Assume $t_1, t_2 \in [t - r, t]$, then

$$\begin{aligned} \|f(x(t_2), u(t_2), t_2)) - f(x(t_1), u(t_1), t_1))\| &= \|[g(x(t_2)) - \eta(u(t_2))] - [g(x(t_1)) - \eta(u(t_1))]\| \\ &\leq \|g(x(t_2)) - g(x(t_1))\| + \|\eta(u(t_2)) - \eta(u(t_1))\| \end{aligned}$$

By the mean value theorem,

$$\begin{aligned} \|[g(x(t_2)) - g(x(t_2))]\| &= g'(c)|t_2 - t_1| \\ &\leq |t_1 - t_2|, \end{aligned}$$

and

$$\begin{aligned} \|\eta(u(t_2)) - \eta(u(t_1))\| &\leq \eta'(c)|t_2 - t_1| \\ &\leq |t_2 - t_1|, t_1 < c < t_2. \end{aligned}$$

Therefore

$$\begin{aligned} \|f(x(t_2), u(t_2)) - f(x(t_1), u(t_1))\| &\leq sup|t_2 - t_1| + sup|t_2 - t_1| \\ &\leq (k_1 + k_2)\rho(t_2, t_1) \\ &= M\rho(t_2, t_1), \end{aligned}$$

and hence $f(x(t), u(t), t)$ is Lipschitzian in the t variable, with Lipschitz constant $M > 0$.

Step (ii):

Consider the bounded closed set $\Gamma^* = [t, \varphi(s); t_0 - r \leq s \leq t, \varphi(t_0) - \beta \leq \varphi(s) \leq \varphi(t_0) + \beta]$ such that $0 \leq \beta k_1 < 1$ is satisfied. Also let $I = [t_0 - r, t]$ be a set, and $\bigcup(I) \subset X$ defined the space of all continuous functions $\omega(s)$ such that

$$\|\omega(s) - \phi(t_0)\| \leq \beta k_1.$$

Then I is a continuous closed bounded subset of X and $\bigcup(I) \subset X$ is compact.

Step (iii):

Using the hypothesis of Krasnoselskii as stated in [4], assume $Q, R : X \to X$, where Q is a contraction and R is continuous with the map RX residing in a compact set I, then

$$f_T(\varphi(t)) = \varphi_0 e^{At} + \varphi(t)e^{-A(t-r)} + A\int_{t-r}^{t} g_T(\varphi(\tau)e^{-A(t-\tau)})d\tau + \int_{t_0}^{t} \eta_T(u(\tau)e^{-A(t-\tau)})d\tau$$

can be express as sum of a contraction and a compact map. That is

$$f_T(\varphi(t)) = Q\varphi(t) + R\varphi(t),$$

with

$$Q(\varphi(t)) = \varphi_0 e^{At} + \int_{t_0}^{t} \eta_T(u(\tau)e^{-A(t-\tau)})d\tau$$

and

$$R(\varphi(t)) = \varphi_t(t)e^{-A(t-r)} + A\int_{t-r}^{t} g_T(\varphi(\tau)e^{-A(t-\tau)})d\tau.$$

Step (iv):

Showing that $R\varphi(t)$ is compact in $X \subset B_H$. Consider the set $\bigcup(I) \subset X$ as defined in step (iii) with metric ℓ on $C[I_i]$, then for $R\varphi(s) \in X, s \in [t_0 - r, t]$

$$\|R\varphi(s) - \varphi(t_0)\| \leq \beta.$$

Also for any continuous functions $\varphi(t_1), \varphi(t_2) \in X,$ for $t_1, t_2 \in [t_0 - r, t]$, then

$$\begin{aligned} \ell(R\varphi(t_2), R\varphi(t_1)) &= sup\|R\varphi(t_2) - R\varphi(t_1)\| \\ &\leq \beta sup\|\varphi(t_2) - \varphi(t_1)\| \\ &\leq \beta k_1 \end{aligned}$$

Thus, $R\varphi(t)$ is compact.

Step (iv):

Showing that $Q\varphi(t)$ map to itself.

Consider any solution $\varphi(t) \in X \subset B_H$ and let Q be a map defined as $Q : \varphi(t) \to \varphi(t)$ such that $Q\varphi(t) = \varphi(t)$, where

$$\varphi(t) = \varphi_0 + \int_{t_0-r}^{t} \eta_T(u(\tau)e^{-A(t-\tau)})d\tau, \text{ for } \varphi_0 = \varphi(t_0)e^{At_0}.$$

Then

$$\begin{aligned} \|\varphi(t) - \varphi_0\| &= \left\| \int_{t_0-r}^{t} \eta_T(u(\tau))e^{-A(t-\tau)})d\tau \right\| \\ &\leq \int_{t_0-r}^{t} \|\eta_T(u(\tau))e^{-A(t-\tau)}\|d\tau \\ &\leq \int_{t_0-r}^{t} k_2 d\tau = k_2|t - (t_0 - r)| \\ &\leq k_2\alpha. \end{aligned}$$

Showing that $Q\varphi(t) = \varphi(t)$ is a contraction: Assume for any arbitrary $\varphi(t_2), \varphi(t_1) \in X \subset B_H$ with $Q\varphi(t_1) = \varphi(t_1), Q\varphi(t_2) = \varphi(t_2)$, and for a metric ℓ on $C[I_i]$ then

$$
\begin{aligned}
\ell(Q\varphi(t_2), Q\varphi(t_1)) &= \ell(\varphi(t_2), \varphi(t_1)) \\
&= sup\left\|(\varphi_0 + \int_{t_0-r}^{t_2} \eta_T(u(\tau)e^{-A(t_2-\tau)})d\tau - (\varphi_0 + \int_{t_0-r}^{t_1} \eta_T(u(\tau)e^{-A(t_2-\tau)})d\tau\right\| \\
&\leq sup\int_{t_0-r}^{t} \left\|(\eta_{T_2}(u(\tau)e^{-A(t_2-\tau)})) - (\eta_{T_1}(u(\tau)e^{-A(t_2-\tau)}))\right\| d\tau \\
&= \leq sup\int_{t_0-r}^{t} sup\|\eta_{T_2}(\tau) - \eta_{T_1}(\tau)\|d\tau \\
&\leq k_2 sup\int_{t_0-r}^{t} d\tau \\
&\leq k_2 sup|t - (t_0 - r)| \\
&= k_2\alpha.
\end{aligned}
$$

Thus, for $f_T(\varphi(t))$ satisfying conditions i-iv, then

$$
f_T(\varphi(t)) = \varphi_0 e^{At} + \varphi_t(t)e^{-A(t-r)} + A\int_{t-r}^{t} g_T(\varphi(\tau)e^{-A(t-\tau)})d\tau + \int_{t_0}^{t} \eta_T(u(\tau)t^{-A(t-\tau)})d\tau,
$$

is the unique T-periodic solution of (3.1).

4.1 EXPONENTIAL ASYMPTOTIC STABILITY

Consider the Laplace transform of (2.1) as

$$
X(s) = (s - se^{-sr} - A)^{-1}x(0) + (s - se^{-sr} - A)^{-1}De^{-sr}, \tag{4.0}
$$

such that

$$
x(t) = L^{-1}((s - se^{-sr} - A)^{-1}x(0) + (s - se^{-sr} - A)^{-1}De^{-sr}), \tag{4.1}
$$

with resolvent matrix

$$
(s - se^{-sr} - A)^{-1}, \tag{4.2}
$$

and state transition matrix

$$
\varphi(t) = L^{-1}\left((s - se^{-sr} - A)^{-1}\right), \tag{4.3}
$$

which mapped the initial state $x(0)$ to the state at time t, and therefore defined the complementary solution

$$
x(t) = \varphi(t)x(0). \tag{4.4}
$$

By the definition of equation (4.3), the stability of system (2.1) largely depends on the resolvent matrix.

Definition 4.1

A matrix $A \in E^{n\times n}$ is called a Metzler matrix if all off-diagonal elements of $-A^{-1}$ are nonnegative (Ngoc, [14]).

Properties of Metzler Matric (Ngoc,[14]):

Suppose $A \in E^{n\times n}$ is a Metzler matrix,

i. then $s(A)$ defined the eigenvalue of A

ii. there exists a non-negative eigenvector $x \neq 0$ such that $Ax = s(A)x$.

iii. given any $\partial \in \mathcal{R}$, there exists a nonzero vector $x \geq 0$ such that $Ax \geq \partial x$ if an only if $s(A) \geq \partial$.

Definitions 4.2

1. System (2.1) is exponentially stable if for any initial value $x(0) = \varphi_0, \|\varphi(t) - \varphi_0\| \leq \varepsilon$, for $\varphi(t)$ defined in equation(4.3)

2. the zero solution of system (2.1) is exponentially asymptotically stable if for any initial value $x(0) = \varphi_0$, $\lim\limits_{t\to\infty} \|\varphi(t), x(0)\| = 0$, for $\varphi(t)$ defined as in equation (4.3)

3. if the zero solution of (2.1) is exponentially asymptotically stable, then the system solution $x(t)$ of equation (4.1) is exponentially asymptotically stable.

4.2 Stability Result

Theorem 4.1

Suppose $A \in E^{n\times n}$ is a Metzler matrix with $\|sI - A\| \neq 0$, such that the resolvent matrix in equation (4.2) is negative, then the zero solution of system (2.1) is exponentially asymptotically stable.

Proof

By the properties of Metzler matrix, if $-A^{-1} > 0$, then the geometric spectrum of A is the set

$$s_{\max} = \{s \in E, \partial \leq s < 0, \text{ such that } |sI - A| \neq 0\} \tag{4.5}$$

Considering the resolvent matrix of equation (4.2), for any $\xi \in \mathcal{R}$, such that $\xi I_n = s(I - e^{-sr})$, then

$$(s - se^{-sr} - A)^{-1} \cong (\xi I_n - A)^{-1}. \tag{4.6}$$

By Crammer's rule, ij entries of equation (4.2) is written as

$$(-1)^{ij}\frac{det\Delta ij}{det(\xi I - A)} = \frac{f_{ij}(\xi)}{X(\xi)} = P(\xi), \tag{4.7}$$

where $f_{ij}(\xi)$ is a polynomial of degree less than n. By implication $P(\xi)$ defined the poles of equation (4.6), and so

$$P(\xi) \cong s_{max}. \tag{4.8}$$

and therefore $(\xi I_n - A)^{-1}$ is stable.

Also by the binomial theorem;

$$\begin{aligned}
(\xi I - A)^{-1} &= \left(\frac{I}{\xi}\right)\left(-\frac{A}{\xi}\right)^{-1} \\
&= \frac{I}{\xi} + \frac{A}{\xi^2} + \frac{A^2}{\xi^3} + \cdots \\
and\varphi(t) &= L^{-1}\left((\xi I - A)^{-1}\right) = I + tA + \frac{(tA)^2}{2!} + \frac{(tA)^3}{3!} + \cdots \\
&= e^{At}.
\end{aligned}$$

By the definition (4.1) of the Metzler matrix, and the approximation of $s_{max} \cong P(\xi)$, the resolvent matrix is negative definite, and

$$\lim_{t\to\infty} \varphi(t) = \lim_{t\to\infty} e^{At} = 0,$$

Then the zero solution of system (2,1) is exponentially asymptotically stable, which implies exponential asymptotical stability of system (2.1).

4.3 Computation of the Delay Bound

In this section, results on the computation of the delay bounds of the system equations to be exponentially stable is presented. Chiasson [5] stated that the asymptotic stability of (2.1) is within certain range of the delay values. The extension of [5] and utilizing the stability theory of section (4.2) (as largely dependent on the state transition matrix), the resolvent matrix is thus used as an approximating tool for evaluation of eigenvalues and the corresponding delay bounds for system (2.1) to be asymptotically stable. Hence

$$P(s, \delta(s)) = (s - s\delta - A)^{-1}, \tag{4.9}$$

which is a two variable polynomial with $\delta = e^{-sr}$. The auxiliary polynomial of equation (4.9) is

$$\bar{P}(s, \delta(s)) = -\delta^m P\left(s, \frac{1}{\delta}\right);\ m = deg\{P(s, \delta)\}.$$

Definition 4.3 (Chiasson, [5])

Let $\{(s_i, \delta_i), i = 1, \ldots, k\}$ be the common zeros of $\left\{P(s, \delta), \bar{P}(x, \delta)\right\}$ for which $Re(s_i) \leq 0, s_i \neq 0$ and $|\delta_i| = 1, \delta_i \neq 1$. Then, for each such pairs $(\delta_i, s_i), r^* = min_{r>0}\{r \in \mathcal{R}/\delta_i = e^{-rs_i}\}$ defines the minimum bound of r_i.

5.1 Controllability Result

The aim of this section is to developed theorems on the null controllability of system (2.0) for any initial condition $\varphi(t_0) = \varphi_0$, given a control function $u(t)$, by using the linear ordinary control system and the free control system of (2.1).

Hence, Hermes and LaSalle [6] defined the associated linear ordinary control system of (2.0) as

$$\begin{aligned} \dot{x}(t) &= Ag(t, x(t)) + Du(t) \\ x(t_0) &= \varphi_0, \end{aligned} \tag{5.1}$$

and its corresponding integral trajectory as

$$f_T(t, t_0, \varphi_0, u) = \varphi_0 e^{At} + \int_{t_0}^{t-T} De^{At(t-\tau)} u(\tau) d\tau,$$

The conditions for properness of (5.1) as stated in (6) is that the free system of (2.0) written

$$\frac{d}{dt} L(t, x_t(t)) = Ag(t, x(t)). \tag{5.2}$$

for

$$L(t, x_t(t)) = x(t) - (x(t - r)),$$

is uniformly asymptotically stable, then system (2.0) is null controllable.

Definition 5.1

i. **Proper System**

The system (5.1) is said to be proper on $[t_0, t_1]$ if for any vector $x \in E^{n\times 1}$, there exists a linear span of $De^{-A\tau}$ defined as $\langle x, De^{-A\tau}\rangle = 0, \tau \in [t_0, t_1]$, almost everywhere, and
rank $[D : AD : A^2D \ldots : A^{n-1}D] = n$.

ii. **Complete Controllability**

The system (5.1) is completely controllable on $[t_0, t_1]$ if for any initial function $\varphi(t_0) = \varphi_0$, there exists a control (input) function $u(t) \in E^{n\times 1}$, which is compact and can transfer the function to another state $\varphi(t_1) = \varphi_1$ in a finite time t_1.

iii. **Null Controllability**

System (5.1) is null controllable on $[t_0, t_1]$, if for any $t_1 > t_0$, there is an admissible control function $u(.) : [t_0, t_1] \to E^{m\times 1}$ that transfer the periodic solution $f_T(t_0, \varphi_0, u, \tau) = x_0$ to $f_T(t_1, \varphi_1, u, \tau) = x_1$ for $\tau \in [t_0, t_1]$.

iv. **Reachable Set**

The state of the system $x_1 \in E^n$, is reachable on $[t_0, t_1]$ if the exists an input function $u(.) : [t_0, t_1] \to E^{n\times 1}$ that transfer (x_0, t_0) to (x_1, t_1). The reachable set $R_1 \subseteq E^n$ is the set of points reachable in t seconds such that

$$R_t = \int_{t_0}^{t_1} e^{A(t_1-\tau)} Du(\tau)d\tau. \tag{5.3}$$

Lemma 5.1

If the corresponding input trajectories of the linear control system of (5.1) takes values in the lager Hilbert space of integrable functions, such that $u(.) : [t_0, t_1] \to E^{m\times 1}$, for $t_1 \geq t_0$, then asymptocially proper system is controllable.

Proof:

Assume system (5.1) is asymptotically proper, using the result of [6], the integral trajectory of the linear ordinary control system is

$$\varphi_0 e^{At_1} + \int_{t_0}^{t_1} De^{A(t_1-\tau)} u(\tau)d\tau = 0,$$

so that

$$\varphi_0 = \int_{t_0}^{t_1} De^{-A\tau} u(\tau)d\tau.$$

Then, by definition (5.0-i), there exists a vector matrix $x \in E^n$ that span $De^{-A(t-\tau)}$ such that,

$$\left.\begin{array}{l} \int_{t_0}^{t} x^{T^*} De^{-A\tau} u(\tau) d\tau = 0, \\ \text{and} \\ x^{T^*} De^{-A\tau} u(\tau) = 0, \end{array}\right\} \tag{5.4}$$

hold almost everywhere.

By the properness assumption of lemma (5.1), if $u(t) \in \big(L([t_0, t_1], E^{n\times 1}), \langle ., . \rangle\big)$, then equation (5.4) is satisfied if and only

$$\langle x^T, De^{-At} \rangle = 0. \tag{5.5}$$

Defining

$$\chi(t) = \langle x, De^{-At} \rangle >= 0,$$

so that

$$\frac{d^{n-1}}{dt^{n-1}} \chi(t) = x^T [(A)^k De^{-At}] = 0, \text{ for } k = 0, 1, 2, \ldots, (n-1). \tag{5.6}$$

Evaluating equation (5.6) at $t = 0$, for $k = 0, 1, 2, \ldots, n-1$, the controllability matrix is obtained as

$$\omega = [D : AD : A^2 D : A^3 D : \ldots : A^{n=1} D]. \tag{5.7}$$

Algebraically, system (5.6) has a solution if $\langle x, \omega \rangle$ has n-linearly independent vector, and hence

$$\text{rank } [D : AD : A^2 D : A^3 D : \ldots : A^{n-1} D] = n.$$

This implies controllability of system (2.1), hence the hypothesis of the Lemma (5.0) holds.

Definition 5.2

1. The reachability map on $[t_1, t_0]$ of the pair of matrices $(A(.), B(.))$ is the function

$$\begin{array}{l} R_t : L([t_0, t_1], E^n) \to E^n, \\ u \to \int_{t_0}^{t_1} e^{A(t_1-\tau)} Du(\tau) d\tau. \end{array} \tag{5.8}$$

2. **Adjoint of a Linear Map**

   Let $(U, F, \langle ., . \rangle)$ and $(V, F, \langle ., . \rangle)$ be Hilbert spaces and $H : U \to V$ is a continuous linear map, the adjoint of H is the linear map $H^* : V \to U$ defined by $\langle v, Du \rangle = \langle D^* v, u \rangle$, for all $u \in U, v \in V$.

3. **Self Adjoint**

   Let $(U, F, \langle ., . \rangle)$ and $H : U \to U$ be linear and continuous, H is called a self adjoint if and only if $H = H^*$, such that for $v, u \in U \langle v, D(u) \rangle = \langle D(v), u \rangle$.

   Therefore for the reachable set R_t of (5.3), assume $e^{A(t-\tau)}D = G(t), t \in [t_0, t_1]$, and $x \in V$, then

$$\begin{aligned}
\langle x, R_t \rangle &= \langle x, G(t)u \rangle = x^T \left(\int_{t_0}^{t_1} G(t)u(t)dt \right) \\
&= \int_{t_0}^{t_1} x^T G(t)u(t)dt \\
&= \int_{t_0}^{t_1} (G(t)x)^T u(t)dt \\
&= \int_{t_0}^{t_1} G(t)^T x u(t)dt \\
&= \langle G(t)x, u \rangle \\
&= \langle R_t^*, x \rangle.
\end{aligned}$$

Hence the linear map of the adjoint R_t^* is defined

$$R_t^* : E^n \to L([t_0, t_0], E^n)$$

$$\int_{t_0}^{t_1} e^{A(t_1-\tau)} Du(\tau)d\tau \to u. \tag{5.9}$$

Lemma 5.2

The linear mapping $R_t o R_t^* : E^n \to E^n$ between two finite dimensional spaces admit a matrix representation known as the controllability gramian matrix.

$$W(t_0, t_1)] = \int_{t_0}^{t-1} e^{A(t_1-\tau)} DD^T (e^{A(t_1-\tau)})^T d\tau \in E^{n \times n}.$$

Proof:

Using equation (5.9), with definition (5.2), it is shown that $\langle x, R_t \rangle = \langle R_t^*, x \rangle$, and

$$R_t : u \to \int_{t_0}^{t_1} (e^{A(t_1-\tau)}) Du(\tau)d\tau.$$

Let $[R_t(x)](\tau) = e^{A(t_1-\tau)}Dx$, then

$$
\begin{aligned}
[R_t o R_t^*](x) &= \left[\int_{t_0}^{t_1} e^{A(t_1-\tau)} D D^T (e^{A(t_1-\tau)})^T d\tau\right] x \\
&= W(t_0, t_1) x,
\end{aligned}
$$

where $W(t_0, t_1)$ is the gramian matrix.

Theorem 5.1 (Main Result III)

Let $L : J \times E^n \times E^n \to E^n$ be well defined such that $L(t, x_t(t)) = x(t) - \rho(t, x(t-r))$, and system (2.0) is equivalent to

$$
\begin{aligned}
&\tfrac{d}{dt} L(t, x_t) = Ax(t) + Du(t) \\
&x(0) = \varphi_0 \\
&\text{such that } y(t) = Cx(t),
\end{aligned}
\tag{5.10}
$$

with a transfer function $C[sI - se^{-sr} - A]^{-1} D$. Then system (2.0) is null controllable if

i. the gramian matrix $W(t_0, t_1) = \int_{t_0}^{t_1} e^{A(t-\tau)} D D^T e^{A(t-\tau)^T} d\tau$, is nonsingular,

ii. system (5.10) is asymptotically proper.

iii. the controllable matrix $w = [D : AD : \ldots : A^{n=1}]$ has a canonical form,

iv. the transfer function has no zero/pole cancellation.

Proof

Consider the gramian matrix

$$
W(t_0, t_1) = \int_{t_0}^{t_1} e^{A(t-\tau)} D D^T e^{A(t-\tau)^T} d\tau,
$$

such that matrices $D = (d_{ij})$ and $D^T = (b_{ij})$, for $b_{ij} = d_{ji}$. Then

$$
|D| = \sum_{\delta \in S_n} (sgn\ \partial) d_{1\delta(1)} d_{2\delta(2)} \ldots d_{n\delta(n)},
$$

and

$$
\begin{aligned}
|D^T| &= \sum_{\delta \in S_n} (sgn \partial) b_{1\delta(1)} b_{2\delta(2)} \ldots b_{n\delta(n)} \\
&= \sum_{\delta \in S_n} (sgn \partial) d_{\delta(1)1} d_{\delta(2)2} \ldots b_{\delta(n)n} \\
&= \sum_{\delta \in S_n} (sgn \partial^{-1}) d_{1\delta^{-1}(1)} d_{2\delta^{-1}(2)} \ldots b_{n\delta^{-1}(n)}
\end{aligned}
$$

where S_n is the set of permutation, ∂ is the permutation and

$$sgn\ \partial = \begin{cases} 1, \text{ if } \partial \text{ is even} \\ -1, \text{ if } \partial \text{ is odd} \end{cases}$$

Let $\vartheta = \partial^{-1}$ be the inverse permutation of ∂, and also $sgn\partial^{-1} = sgn\partial$, therefore $sgn\partial^{-1} = sgn\vartheta = sgn\partial$. Hence,

$$\begin{aligned} |D^T| &= \sum_{\delta \in S_n} (sgn\partial^{-1}) d_{1\delta^{-1}(1)} d_{2\delta^{-1}(2)} \dots b_{n\delta^{-1}(n)} \\ &= \sum_{\delta \in S_n} (sgn\vartheta) d_{1\Im(1)} d_{2\Im(2)} \dots b_{n\Im(n)} \\ &= |D|. \end{aligned}$$

Therefore by the definition of the gramian matrix,

$$W(t_0, t_1) = \int_{t_0}^{t_1} e^{A(t-\tau)} D D^T e^{A(t-\tau)^T} d\tau = \int_{t_0}^{t_1} \|e^{A(t-\tau)} D\|^2 d\tau \geq 0. \tag{5.11}$$

Since D is nonsingular by its properties, then

$$W(t_0, t_1) \neq 0,$$

and hypothesis (i) of the theorem is proved. Also by lemma (5.0) condition (ii) is satisfied.

Proving (iii) using (ii); assume the controllable matrix $w = [D : AD : \dots : A^{n=1}D]$ has C_k invariant cyclic subspace decomposition, with distinct eigenvalues, then w is diagonalizable with diagonal matrix

$$w = \begin{bmatrix} C_{m_1} & 0 & \dots & 0 \\ 0 & C_{m_2} & \dots & 0 \\ \vdots & & \vdots & \\ 0 & \dots & \dots & C_{m_k} \end{bmatrix},$$

where C_{m_k} defined the $\ker(w - s_k)$. Then, the characteristic polynomial of w is,

$$w(t) = m_1(t) + m_2(t) + \cdots m_k(t),$$

($m_k(t)$ is monic), with minimal polynomial,

$$m_w(t) = (t - s_1)^{m_1} + (t - s_2)^{m_2} + \cdots (t - s_k)^{m_r}.$$

Hence, the direct sum decomposition of w is

$$\begin{aligned} w &= ker(w-s_1)^{m_1} \oplus ker(w-s_2)^{m_2}, \oplus \ldots \oplus (w-s_k)^{m_r} \\ &= C_1 \oplus C_2 \oplus \ldots \oplus C_k, \end{aligned}$$

where C_k defined the companion matrix. Defining a nilpotent operator $N^n = 0$ for $n \in Z^+$, with a minimum polynomial of index k written as $m_w(t) = (t-0)^{k_1} = t^k$ (clearly has eigenvalue zero), so that C_k can be express in terms of the nilpotent matrix as $C_k = s_k I_{rk} + N$ (I is an $r \times k$ identity matrix, N a nilpotent block) and the canonical form of the controllable matrix w is thus

$$w = s_1 I_{r1} + N \oplus s_2 I_{r2} + N \oplus \ldots \oplus s_k I_{rk} + N. \tag{5.12}$$

Proving (iv); using the transform of equation (4.0) stated as

$$X(s) = (s - se^{-sr} - A)^{-1} x(0) + (s - se^{-sr} - A)^{-1} De^{-sr},$$

such that

$$x(t) = L^{-1}((s - se^{-sr} - A)^{-1} x(0) + (s - se^{-sr} - A)^{-1} De^{-sr}),$$

and the output function

$$y(t) = L^{-1}(C(s - se^{-sr} - A)^{-1} x(0) + C(s - se^{-sr} - A)^{-1} De^{-sr}). \tag{5.13}$$

Then, there exists a mapping of the control function to the reacheable set defined as

$$\begin{aligned} \Im : L([0,t], E^m &\rightarrow E^n \\ u &\rightarrow y, \end{aligned}$$

for

$$\Im_{yu}(s) = (sI - e^{-sr} - A)^{-1} De^{-sr}. \tag{5.14}$$

The function $\Im_{yu}(s)$ is the system transfer function of (5.10).

Algebraically, (5.14) is expressed as

$$\Im_{yu}(s) = \frac{b(s)}{a(s)} = K \frac{(s_1 - z_1) \ldots (s_i - z_i)}{(s_1 - p_1) \ldots (s_i - p_i)},$$

where poles (p_i) and zeros (z_i) are the roots of $a(s)$ and $b(s)$ respectively. Assume $z_i = p_i$, then

$$\lim_{z_i \rightarrow p_i} \Im_{yu} \rightarrow \infty,$$

which contradict the concept of controllability. Therefore $z_i \neq p_i$ (implies no zeros/poles cancellation).

6.1 ILLUSTRATION

Consider the neutral delay model of a partial element equivalent circuit (PEEC) which includes new circuit element consisting of a retarded mutual coupling between the partial inductance of the form $L_p(t-r)$, is without retarded current sources of the form

$$\begin{aligned} &\tfrac{d^2}{dt^2}Q(t) - \tfrac{d^2}{dt^2}Q(t-r)) + a_1\tfrac{d}{dt}Q(t) + a_2Q(t) = du(t) \\ &Q(t_0) = Q_0 \end{aligned} \tag{6.1}$$

with an output function $y(t) = CQ(t)$.

Reducing (6.1) to a first order system of the form

$$\begin{aligned} &\tfrac{d}{dt}(Q(t) - Q(t-r)) = AQ(t) + Du(t), \\ &Q(t_0) = Q_0, \\ &\text{and } y(t) = CQ(t_0) \end{aligned} \tag{6.2}$$

where

$$A = \begin{pmatrix} 0 & 1 \\ -a_1 & -a_2 \end{pmatrix}, \; D = \begin{pmatrix} 0 \\ d_{21} \end{pmatrix}, \; C = (c_1 \; c_2).$$

Exponential Stability Analysis of System (6.2):

By theorem (4.0), A is a stable Metzler matrix ($s(A) < 0$), if $a_2 > \sqrt{a_2^2 - 4a_1}$ such that $-A^{-1} > 0$. Also, by the definition of the resolvent matrix

$$\begin{aligned} P(s,\delta(s)) &= (I(s - se^{-sr}) - A) \\ &= s^2(1 - 2\delta + \delta^2) + a_2 s(\delta - 1) + a_1 \\ \bar{P}(s,\delta(s)) &= -\delta^m P\left(s, \frac{1}{\delta(s)}\right) \\ &= -s^2(1 - 2\delta + \delta^2) - a_2 s(\delta^2 - \delta) - a_1, \end{aligned}$$

where m is the highest degree of δ in $P(s, d(s))$, $\delta = e^{-sr}$.

Solving $P(s,\delta(s))$ and $\bar{P}(s,\delta(s))$ simultaneously to obtained

$$s = -\frac{a_1}{a_2} \text{ and } \delta = \frac{-(a_1a_2^2 - 2a_1^2) \pm \sqrt{(a_1a_2^2 - 2a_1^2)^2 - 4a_1^2(2a_2^2 + a_1^2 - a_1a_2^2)}}{2a_1^2},$$

such that $Re(s_i) \leq 0,\ s_i \neq 0$ and $|\delta_i| = 1, \delta_i \neq 1$ are satisfied, then the system is asymptotically stable. also, for each such pairs of $(\delta_i, s_i),\ r^* = \min_{r>0}\{r \in \mathcal{R}/\delta_i = e^{-rs_i}\}$ defines the minimum delay bounds of r_i for system (4.2) to be asymptotically stable.

Controllability Analysis of System (6.2) on $[t_0, t_1]$, with an initial function $Q(t_0) = Q_0$, control (input) function $Du(t) \in E^{m\times 1}$ and output function $y(t) = CQ(t)$ is as follows:

1. By the proved of hypothesis (i) of theorem (5.1), the gramian matrix
$$W(t_0, t_1) = \int_{t_0}^{t_1} e^{A(t-\tau)} DD^T e^{A(t-\tau)^T} d\tau = \int_{t_0}^{t_1} e^{A(t-\tau)} D d\tau,$$
and
$$\exp A(t-\tau) = \exp \begin{pmatrix} 0 & 1 \\ -a_1 & -a_2 \end{pmatrix} (t-\tau) = [v_1 v_2] \begin{pmatrix} e^{\lambda_1(t-\tau)} & 0 \\ 0 & e^{\lambda_2(t-\tau)} \end{pmatrix} [v_1 v_2]^{-1},$$
so that
$$W(t_0, t_1) = \int_{t_0}^{t_1} [v_1 v_2] \begin{pmatrix} e^{\lambda_1(t-\tau)} & 0 \\ 0 & e^{\lambda_2(t-\tau)} \end{pmatrix} [v_1 v_2]^{-1} D d\tau \neq 0,$$
where v_1, v_2 are the corresponding eigenvectors of the eigenvalues λ_1, λ_2 of matrix A, and hence $W(t_0, t_1)$ is nonsingular.

2. Analysis of hypothesis (ii) of theorem (5.1) for properness property;
$$A = \begin{pmatrix} 0 & 1 \\ -a_1 & -a_2 \end{pmatrix}, D = \begin{pmatrix} 0 \\ d \end{pmatrix},\ AD = \begin{pmatrix} d \\ -a_2 d \end{pmatrix},$$
and
$$\begin{aligned} \text{rank } [D : AD] &= \text{rank} \begin{pmatrix} 0 & d \\ d & -a_2 d \end{pmatrix} \\ &= \text{rank} \begin{pmatrix} d & -a_1 d \\ 0 & d \end{pmatrix} = 2 \ \text{ by elementary rows operation.} \end{aligned}$$
Hence $[D : AD : \ldots : A^{n=1} D]$ is proper with rank 2.

3. Analysis of hypothesis (iii) of theorem (5.1) for canonical form of controllable matrix $w = [D : AD] = \begin{pmatrix} 0 & d \\ d & -a_2 d \end{pmatrix}$ for the appropriate choice of matrices A and D is
$$w = s_1 I_2 + N_2 \oplus s_2 U_1 + N_1$$

where s_1, s_2 are the characteristic roots of the controllable matrix.

4. Analysis of hypothesis (iv) of theorem (5.1) of the transfer function

$$
\begin{aligned}
C(s - s\delta - A)^{-1}D &= \frac{(c_1 c_2)\begin{pmatrix} s - s\delta - a_2 & 1 \\ -a_1 & s - s\delta \end{pmatrix}\begin{pmatrix} 0 \\ d \end{pmatrix}}{s^2(a - 2\delta + \delta^2) + a_2(\delta - 1) + a_1} \\
&= \frac{(c_1(s - s\delta - a_2) - c_2 a_1 \;\; c_1 + c_2(s - s\delta))\begin{pmatrix} 0 \\ d \end{pmatrix}}{s^2(1 - 2\delta + \delta^2) + a_2 s(\delta - 1) + a_1} \\
&= \frac{(c_1 + c_2(s - s\delta))d}{s^2(1 - 2\delta^2) + a_2 s(\delta - 1) + a_1},
\end{aligned}
$$

which has no zero/pole cancellation?

Hence by analysis i - iv, and for the appropriate choice of matrices A, D, and C, system (6.2) is controllable.

7.1 Conclusion

The periodic solution of a linear neutral system with an input function and initial value was obtained by employing the variation of constant method. theory on uniqueness of the obtained solution was established and proved by utilizing Burton [4] inversion theory of a perturbed differential operator which yields the sum of a contraction and a compact map. The resolvent matrix of the system equation (which must be negative definite) was used as a tool to analyze the exponential stability of the system equation and the computation of the maximum value of the delay bounds for the system to be asymptotically stable. The controllability of the system was studies by the analyses of the linear ordinary control and the free control parts of the linear neutral system:- for properness, non-singularity of the gramian matrix, canonical form of the controllable matrix and the non zero/pole cancellation of the transfer function matrix. Results obtained were employed on neutral delay model of a partial element equivalent circukt (PEEC) consisting of a retarded mutual coupling between the partial inductance which confirmed the stuitability of the test.

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