Exponential stability of periodic solutions in inertial neural networks with unbounded delay

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Abstract—In this paper, the exponential stability of periodic solutions in inertial neural networks with unbounded delay are investigated. First, using variable substitution the system is transformed to first order differential equation. Second, by the fixed-point theorem and constructing suitable Lyapunov function, some sufficient conditions guaranteeing the existence and exponential stability of periodic solutions of the system are obtained. Finally, two examples are given to illustrate the effectiveness of the results.

Keywords—inertial neural networks, unbounded delay, fixed-point theorem, Lyapunov function, periodic solutions, exponential stability.

I. INTRODUCTION

CELLULAR neural networks (CNNs) [1,2] have been successfully applied in signal processing, pattern recognition, especially in static image treatment [3]. In delayed neural networks, a constant delay is only a special case. In most situations, delays are variable, and in fact unbounded. In some practical applications and hardware implementations of neural networks, the inevitable time delay may be unbounded, for example

\[
\frac{dx_i(t)}{dt} = -\alpha_i x_i(t) + \sum_{j=1}^{n} a_{ij} f_j(x_j(t)) + \sum_{j=1}^{n} b_{ij} f_j(x_j(t-\tau_{ij})) + \sum_{j=1}^{n} c_{ij} \int_{-\infty}^{t} K_{ij}(t-s) f_j(x_j(s)) ds + I_i(t),
\]

for \(i = 1, 2, \ldots, n\).

Therefore, the studies of neural networks with time-varying delays and unbounded time delays are more important and necessary than those with constant delays, and the corresponding research can be seen in [4-14].

On the other hand, the inertia can be considered a useful tool that is added to help in the generation of chaos in neural systems. Babcock and Westervelt [15] combined inertia and driving to explore chaos in one- and two-neuron systems. Tani et al. [16-18] added inertia and a nonlinear oscillating resistance to neural equations as a way of chaotically searching for memories in neural networks. In [19], the authors considered the bifurcation and chaos in a single inertial neuron model with both time delay and inertial term. Liu et al. [20-23] investigated the Hopf bifurcation and dynamics of an inertial two-neuron system or in a single inertial neuron model. In [24], the authors investigate the dynamical characteristics of a single inertial neuron model with time delay under periodic external. Ke and Miao [25-26] investigate stability of equilibrium point and periodic solutions for in inertial BAM neural networks with time delay and unbounded delay, respectively.

In this paper, we will investigate the exponential stability of periodic solutions for the following inertial neural networks with unbounded delay.

\[
\frac{dx_i(t)}{dt} = -\beta_i x_i(t) + \alpha_i x_i(t) + \sum_{j=1}^{n} a_{ij} f_j(x_j(t)) + \sum_{j=1}^{n} b_{ij} f_j(x_j(t-\tau_{ij})) + \sum_{j=1}^{n} c_{ij} \int_{-\infty}^{t} K_{ij}(t-s) f_j(x_j(s)) ds + I_i(t),
\]

for \(i = 1, 2, \ldots, n\), where the second derivative are called an inertial term of system (2), \(\alpha_i, \beta_i > 0\) are constants. \(x_i(t)\) denotes the states variable of the \(i\)th neuron at the time \(t\), \(a_{ij}\), \(b_{ij}\) and \(c_{ij}\) are connection weights of the neural networks, \(f_j\) denotes the activation functions of \(j\)th neuron at the time \(t\), \(\tau_{ij}\) is time delay of \(j\)th neuron at the time \(t\) and satisfies \(0 \leq \tau_{ij} \leq \tau\), \(I_i(t)\) denotes the external inputs on the \(i\)th neuron at the time \(t\), \(K_{ij} : R^+ \rightarrow R^+\) are continuous functions, and satisfy \(\int_{0}^{\infty} e^{\eta t} K_{ij}(s) ds = \rho_{ij}(\eta), i, j = 1, 2, \ldots, n\), where \(\rho_{ij}(\eta)\) are continuous functions in \([0, \delta])(0 < \delta < 1)\) and \(\rho_{ij}(0) = 1\).

The initial values of system (2) are

\[x_i(s) = \varphi_i(s), \frac{dx_i(s)}{dt} = \psi_i(s), i = 1, 2, \ldots, n,\]

where \(-\tau \leq s \leq 0, \varphi_i(s), \psi_i(s)\) are bounded and continuous function.

Based on the standpoint of Mathematics and Physics, the system (2) is a two-order nonlinear dynamic system, and \(\beta_i > 0\) is a damping coefficient. Then the neural networks of system (1) can be understood as a model which damping tends to infinity. But in some practical problems, we need to consider the existence and stability of periodic solution of the system when it has damping(or low damping). For example, pendulum equation with dissipation term

\[\frac{d^2x(t)}{dt^2} = -\alpha \frac{dx(t)}{dt} - \beta x - \gamma \sin t,\]

and forced Duffing equation

\[\frac{d^2x(t)}{dt^2} = -\alpha \frac{dx(t)}{dt} - x(\beta x + \gamma x^2) + \delta \cos t,\]

which have applied background.

II. PRELIMINARIES

Throughout this paper, we make the following assumptions.
\( (H1) \): The activation functions \( f_j \) satisfy Lipschitz condition, i.e., there exist constant \( L_j > 0 \), such that
\[
|f_j(v_1) - f_j(v_2)| \leq L_j|v_1 - v_2|, \\
\]
j = 1, 2, \ldots, n, v_1, v_2 \in R, and there exist constant \( \bar{f}_j > 0 \), such that
\[
0 \leq |f_j(x)| \leq \bar{f}_j, f_j(0) = 0, j = 1, 2, \ldots, n, x \in R.
\]

\( (H2) \): \( I_i(t) \) are \( \omega \)- periodic continuously functions and satisfy \( |I_i(t)| \leq \bar{I}_i, i = 1, 2, \ldots, n, t \in R. \)

Let variable transformation:
\[
y_i(t) = \frac{dx_i(t)}{dt} + x_i(t), \quad i = 1, 2, \ldots, n,
\]
then of (2) and (3) can be rewritten as
\[
\begin{cases}
\frac{dx_i(t)}{dt} = -x_i(t) + y_i(t), \\
\sum_{j=1}^n \frac{dx_j(t)}{dt} = -(1 + \alpha_i - \beta_i)x_i(t) - (\beta_i - 1)y_i(t) \\
\sum_{j=1}^n a_{ij}f_j(x_j(t)) + b_{ij}f_j(x_j(t - \tau_{ij})), \\
\sum_{j=1}^n c_{ij}\int_0^\infty K_{ij}(t-s)f_j(x_j(s))ds + I_i(t)
\end{cases}
\]
for \( i = 1, 2, \ldots, n, \)
and
\[
\begin{cases}
x_i(s) = \phi_i(s), \\
y_i(s) = \psi_i(s)
\end{cases}
\]
satisfy
\[
\|\phi - \psi\|^2 = \sup_{-\tau \leq t \leq 0} \sum_{i=1}^n |\phi_i(t) - \psi_i(t)|^2.
\]

\textit{Definition 2:} Let vector \( u = (u_1, u_2, \ldots, u_n)^T \) and matrix \( B = (b_{ij})_{n \times n} \), we define norm
\[
\|u\|^2 = \sum_{i=1}^n u_i^2, \quad ||B||^2 = \sum_{i,j=1}^n b_{ij}^2.
\]

Let \( d_i = \sum_{j=1}^n f_j([a_{ij}] + [b_{ij}] + [c_{ij}]) + \bar{I}_i, \)
\[
e = \min \{d_i\}, \\
h_i = \max \left\{ \frac{2\alpha_i}{\sqrt{\beta_i} - 4\alpha_i}, \sqrt{\beta_i} - 4\alpha_i \right\}, \\
k_i = \psi_i(0) + \frac{1}{\beta_i}[\alpha_i h_i + \sum_{j=1}^n f_j([a_{ij}]) + \sum_{j=1}^n f_j([b_{ij}]) + \sum_{j=1}^n f_j([c_{ij}]) + \bar{I}_i], \\
h = \min \left\{ \frac{3\beta_i^2 + 2\beta_i e}{2}, \right\}
\]
for \( i = 1, 2, \ldots, n. \)

\textit{Lemma 3:} For system (2), under hypotheses \( (H1) - (H2) \), if \( \beta^2 - 4\alpha_i \neq 0, \psi_i(0) > 0, \psi_i(0) \geq \frac{e}{\alpha_i} > 0, i = 1, 2, \ldots, n, \)
then \( x(t) \) and \( \frac{dx_i(t)}{dt} \) is bounded, and
\[
|x_i(t)| \leq h_i, \quad \frac{dx_i(t)}{dt} \leq k_i, i = 1, 2, \ldots, n.
\]

\textit{Proof:} From (2), we obtain
\[
\frac{d^2x_i(t)}{dt^2} + \beta_i \frac{dx_i(t)}{dt} + \alpha_i x_i(t)
\]
\[
\leq \sum_{j=1}^n f_j([a_{ij}]) + [b_{ij}] + [c_{ij}] + \bar{I}_i, \quad i = 1, 2, \ldots, n.
\]

We consider the following differential equations
\[
\frac{d^2x_i(t)}{dt^2} + \beta_i \frac{dx_i(t)}{dt} + \alpha_i x_i(t) = e, \quad i = 1, 2, \ldots, n.
\]

If \( \beta_i^2 - 4\alpha_i > 0 \), We obtain general solution of (7)
\[
x_i(t) = C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t} + \frac{e}{\alpha_i}, \quad i = 1, 2, \ldots, n,
\]
where
\[
\lambda_1 = \frac{1}{2}[-\beta_i + \sqrt{\beta_i^2 - 4\alpha_i}] < 0, \\
\lambda_2 = \frac{1}{2}[-\beta_i - \sqrt{\beta_i^2 - 4\alpha_i}] < 0, \\
C_1, C_2 \) are arbitrary constant.

For initial values \( x_i(0) = \phi_i(0), \frac{dx_i(0)}{dt} = \psi_i(0), \) if \( \psi_i(0) > 0, \phi_i(0) \geq \frac{e}{\alpha_i} > 0, \) we can obtain,
\[
C_1 = \frac{\sqrt{\beta_i^2 - 4\alpha_i} |\phi_i(0) - \lambda_2(\phi_i(0) - e/\alpha_i)|}{\beta_i^2 - 4\alpha_i} > 0, \\
C_2 = \frac{1}{\sqrt{\beta_i^2 - 4\alpha_i}} |\phi_i(0) - \lambda_1(\phi_i(0) - e/\alpha_i)| < 0.
\]

We have
\[
|x_i(t)| \leq \frac{1}{\sqrt{\beta_i^2 - 4\alpha_i}} |\phi_i(0) - \lambda_2(\phi_i(0) - e/\alpha_i)| - \lambda_1(\phi_i(0) - e/\alpha_i) + \psi_i(0) + \frac{e}{\alpha_i}
\]
\[
\leq \frac{2\alpha_i}{\sqrt{\beta_i^2 - 4\alpha_i}} |\phi_i(0) - \lambda_2(\phi_i(0) - e/\alpha_i)| + \frac{e}{\alpha_i} \leq h_i, \quad i = 1, 2, \ldots, n.
\]

If \( \beta_i^2 - 4\alpha_i < 0 \), We obtain general solution of (7)
\[
x_i(t) = e^{-\beta_i/2t}[C_1 \cos \frac{\sqrt{4\alpha_i - \beta_i^2}}{2} t + C_2 \sin \frac{\sqrt{4\alpha_i - \beta_i^2}}{2} t + \frac{e}{\alpha_i}], \quad i = 1, 2, \ldots, n,
\]
where $C_1, C_2$ are arbitrary constant.

For initial values $x_i(0) = \phi_i(0)$, $\frac{dx_i}{dt}(0) = \psi_i(0)$, if $\psi_i(0) > 0$, $\phi_i(0) \geq \frac{\alpha_i}{\beta_i} > 0$, we can obtain,

$C_1 = \phi_i(0) - \psi_i(0)$, $C_2 = \frac{1}{\sqrt{\beta_i^2 - 4\alpha_i}}[2\psi_i(0) + \beta_i(\phi_i(0) - \psi_i(0))] > 0$.

We have

$$|x_i(t)| \leq \frac{\phi_i(0) - \psi_i(0)}{\alpha_i} + \frac{1}{\sqrt{\beta_i^2 - 4\alpha_i}}[2\psi_i(0) + \beta_i(\phi_i(0) - \psi_i(0)) + \frac{1}{\alpha_i}]$$

$$\leq \frac{2\psi_i(0) + \beta_i(\phi_i(0) - \psi_i(0))}{\sqrt{\beta_i^2 - 4\alpha_i}} + \frac{\psi_i(0)}{\alpha_i} \leq h_i, i = 1, 2, \ldots, n.$$

On the other hand, from (2), we have

$$\frac{d}{dt}e^{\beta_i t}x_i(t) = e^{\beta_i t}(-\alpha_i x_i(t) + \sum_{j=1}^{n} a_{ij} f_j(x_j(t)) + \sum_{j=1}^{n} \int_{-\infty}^{x_j} K_{ij}(t-s) f_j(x_j(s)) ds + I_i(t),$$

for $i = 1, 2, \ldots, n$. We obtain

$$\frac{dx_i}{dt} = e^{-\beta_i t}\psi_i(0) + \int_{0}^{t} e^{\beta_i(t-u)}[-\alpha_i x_i(u) + \sum_{j=1}^{n} a_{ij} f_j(x_j(u)) + \sum_{j=1}^{n} \int_{-\infty}^{x_j} K_{ij}(u-s) f_j(x_j(s)) ds + I_i(u)] du,$$

for $i = 1, 2, \ldots, n$. Since $|x_i(t)| \leq h_i$, from the above equation, we obtain

$$\frac{dx_i}{dt} \leq \phi_i(0) + \int_{0}^{t} e^{\beta_i(t-u)}[a_{ij} h_i + \sum_{j=1}^{n} f_j(|a_{ij}|)]$$

$$+ [b_{ij} + |c_{ij}|] du \leq \psi_i(0) + \frac{1}{\alpha_i} |\alpha_i h_i + \sum_{j=1}^{n} f_j(|a_{ij}|) + |b_{ij}| + |c_{ij}| + I_i| du$$

$$= k_i, i = 1, 2, \ldots, n.$$

Proof of completion of Lemma 3.

**Lemma 4.** For matrix

$$A_i = \begin{pmatrix}
-1 & 0 & \cdots & 0 \\
\beta_i - \alpha_i & -1 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & -1 \\
\end{pmatrix}, i = 1, 2, \ldots, n.$$

we have

$$\|\exp(-A_i t)\| \leq M_i e^{\mu_i t}, i = 1, 2, \ldots, n,$$

where, 1) if $\beta_i^2 - 4\alpha_i > 0 (i = 1, 2, \ldots, n)$, then

$$\mu_i = \frac{1}{2} [\beta_i + \sqrt{\beta_i^2 - 4\alpha_i}],$$

$$M_i = \frac{4\beta_i}{\beta_i^2 - 4\alpha_i} \frac{1}{e^{\beta_i t}},$$

$$N_i = \frac{\beta_i^2 - 4\alpha_i}{2\beta_i e^{\beta_i t}} \left( e^{\beta_i t} - e^{\frac{\beta_i t}{2}} \right),$$

$$\cdot \left( 1 + \frac{\beta_i}{\beta_i^2 - 4\alpha_i} \right),$$

$$2) \text{if} \beta_i^2 - 4\alpha_i < 0 (i = 1, 2, \ldots, n),$$

$$\mu_i = \frac{1}{2} \beta_i,$$

$$M_i = \frac{2}{\beta_i} \frac{1}{e^{\beta_i t}},$$

$$N_i = \frac{\beta_i^2 - 4\alpha_i}{2\beta_i e^{\beta_i t}} \frac{1}{e^{\beta_i t}},$$

$$\cdot \left( 1 + \frac{\beta_i}{\beta_i^2 - 4\alpha_i} \right) + \frac{\beta_i^2}{\beta_i^2 - 4\alpha_i}.$$
we can obtain
\[
\| (\exp(-A_0 \omega) - E)^{-1} \| \leq \delta \| (\exp(\omega d_0 - \exp(\lambda_1 \omega \delta - \delta e^{-\delta \omega}) - e^{-\delta \omega})) \| (1 - \lambda_1)^2 \\
+ (1 - \lambda_2)^2 (1 - \lambda_2^2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \\
- (1 - \lambda_2)^2 (a_1 + a_2) w^2 + (2 \lambda_2^2 + 1 - \lambda_2)^2 (1 - \lambda_2^2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \\
+ (2 \lambda_2^2 + 1 - \lambda_2)^2 (a_1 + a_2) w^2 + (2 \lambda_2^2 + 1 - \lambda_2)^2 (1 - \lambda_2^2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \\
\leq \delta \| (\exp(\omega d_0 - \exp(\lambda_1 \omega \delta - \delta e^{-\delta \omega}) - e^{-\delta \omega})) \| (1 - \lambda_1)^2 \\
+ (2 \lambda_2^2 + 1 - \lambda_2)^2 (a_1 + a_2) w^2 + (2 \lambda_2^2 + 1 - \lambda_2)^2 (1 - \lambda_2^2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \\
\leq \delta (2 \lambda_2^2 + 1 - \lambda_2)^2 \left[ (a_1 + a_2) w^2 + (2 \lambda_2^2 + 1 - \lambda_2)^2 (1 - \lambda_2^2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \right].
\]

If \( \beta_1^2 - 4a_1 \beta_1 < 0 \), let \( \delta = \frac{1}{2} \sqrt{4a_1 - \beta_1^2} \), we obtain the fundamental solution matrix of (8) is
\[
\phi(t) = e^{\beta_1 t/2} \begin{bmatrix}
\cos \delta t \\
\sin \delta t \\
(1 - \frac{\beta_1}{2}) \sin \delta t + \delta_1 \sin \delta t \\
(1 - \frac{\beta_1}{2}) \sin \delta t - \delta_1 \cos \delta t
\end{bmatrix}.
\]

By calculation, we obtain
\[
\phi_1^{-1}(0) = \frac{1}{\delta_1} \left[ \frac{\delta_1}{\lambda_1 - \frac{\beta_1}{2}} - 1 \right].
\]

Since \( \exp(-A_1 t) = \phi(t) \phi_1^{-1}(0) \), we have
\[
\exp(-A_1 t) = \frac{1}{\delta_1^2} \begin{bmatrix}
\delta_1 \cos \delta t + (1 - \beta_1) \sin \delta t \\
\delta_1 \cos \delta t - (1 - \beta_1) \sin \delta t \\
- \sin \delta t \\
(1 - \frac{\beta_1}{2}) \sin \delta t + \delta_1 \cos \delta t
\end{bmatrix}.
\]

Then we have
\[
\| \exp(-A_1 t) \| \leq \delta_1 \| \exp(\omega d_0 - \exp(\lambda_1 \omega \delta - \delta e^{-\delta \omega}) - e^{-\delta \omega})) \| \left[ (1 - \lambda_1)^2 \\
+ (1 - \lambda_2)^2 (1 - \lambda_2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \\
+ (2 \lambda_2^2 + 1 - \lambda_2)^2 (a_1 + a_2) w^2 + (2 \lambda_2^2 + 1 - \lambda_2)^2 (1 - \lambda_2 - \lambda_2^2 - 1)^2 (a_1 + a_2) w^2 \right].
\]

III. MAIN RESULTS

In this section, we will derive some sufficient conditions which ensure the existence and the exponential stability of periodic solution for system (2).

Let
\[
X = \{ x = (x_1(t), x_2(t), \ldots, x_n(t))^T \} \\
\in C(R, R^n) : x(t) + w = x(t), t \in R.
\]

\[
Y = \{ y = (y_1(t), y_2(t), \ldots, y_n(t))^T \} \\
\in C(R, R^n) : y(t) + w = y(t), t \in R.
\]

Defined
\[
\| z_i \| = \max_{t \in [0, T]} \| z_i(t) \|, \quad \| z \| = \max_{1 \leq i \leq n} \{ \| z_i \| \}.
\]

Define the cone \( P \) in \( X \) by
\[
P = \{ z = (x(t), y(t))^T \} : x, y \in X : \| z_i(t) \| \leq h_i, |y_j| \leq k_j, \quad i = 1, 2, \ldots, n \},
\]

\[
|y_j| \leq k_j, \quad i = 1, 2, \ldots, n,
\]

then system (2) has a unique \( \omega \)-periodic solution.

Proof. Let the map \( T \) be defined by
\[
(Tz)_i(t) = (Tz_1)_i(t), (Tz_2)_i(t), \ldots, (Tz_n)_i(t),
\]

\[
z \in P, t \in R, \text{ where for } i = 1, 2, \ldots, n,
\]

\[
(Tz_i)_i(t) = \left[ \exp(-A_0 \omega) - E \right]^{-1} \int_t^{t + \omega} \exp(-A_0(s - t))(Tz_i)_i(s) ds.
\]

Since \( F_i(z_i(s) + w) = F_i(z_i(s)), |x_i(t)| \leq h_i, i = 1, 2, \ldots, n \), for any \( z \in P \), from (9), we obtain
\[
(Tz_i)_i(t + \omega) = \left[ \exp(-A_0 \omega) - E \right]^{-1} \int_t^{t + \omega} \exp(-A_0(s - t))(Tz_i)_i(s) ds
\]

\[
= \left[ \exp(-A_0 \omega) - E \right]^{-1} \int_t^{t + \omega} \exp(-A_0(s - t)) F_i(z_i(s)) ds
\]

\[
\times F_i(z_i(s)) ds = (Tz_i)_i(t).
\]

By Lemma 4, we have
\[
\| (Tz_i) \| = \max_{0 \leq t \leq \omega} \| (Tz_i)_i(t) \|
\]

\[
= \max_{0 \leq t \leq \omega} \left[ \left\| \exp(-A_0 \omega) - E \right\|^{-1} \int_t^{t + \omega} \exp(-A_0(s - t)) F_i(z_i(s)) ds \right].
\]
Now we will show that all the conditions of Theorem 5 are satisfied, thus, the conditions of Theorem 5 are satisfied, and the system (2) has a unique ω-periodic solution which exponentially stable.

Proof. By using Theorem 5, system (2) has a unique ω-periodic solution. In the following we will prove the unique positive ω-periodic solution is exponentially stable. Let 
\[ x^\nu(t) = (x_1^\nu(t), x_2^\nu(t), \ldots, x_n^\nu(t))^T \] be an ω-periodic solution of system (2) with initial value 
\[ x_i(0) = \varphi_i(s), \quad \frac{dx_i}{ds}(s) = \psi_i(s), \quad i = 1, 2, \ldots, n, \quad -\tau \leq s \leq 0. \]
Let \( y^\nu(t) = x^\nu(t) + \frac{dx^\nu}{ds}(t) \), \( u_i(t) = x_i(t) - x_1^\nu(t), \) \( v_i(t) = y_i(t) - y_1^\nu(t), \) \( \bar{f}_i(u_i(t)) = f_i(x_i(t)) - f_1(x_1^\nu(t)), \)
for \( i = 1, 2, \ldots, n. \)

From (4), we can obtain
\[
\begin{aligned}
\frac{du_i}{dt} & = -u_i(t) + v_i(t), \\
\frac{dv_i}{ds} & = -(\beta_i - \beta_1)u_i(t) + \sum_{j=1}^{\infty} a_{ij}f_j(u_j(t)) \\
& \quad + \sum_{j=1}^{\infty} b_{ij}\bar{f}_j(u_j(t) - \tau_j)) \\
& \quad + \sum_{j=1}^{\infty} c_{ij}\int_{-\infty}^{\infty} K_{ij}(t-s)\bar{f}_j(u_j(s))ds.
\end{aligned}
\]
for \( i = 1, 2, \ldots, n. \)

From (10), we get
\[
\begin{aligned}
&\frac{1}{2}\frac{d}{dt}(u_i^2(t) + v_i^2(t)) = -u_i^2(t) + u_i(t)v_i(t) \\
&\quad - (1 + \alpha_i - \beta_i)u_i(t)v_i(t) - (1 - \beta_i - \beta_1)u_i(t)^2 \\
&\quad + \sum_{j=1}^{\infty} a_{ij}v_j(t)\bar{f}_j(u_j(t)) + \sum_{j=1}^{\infty} b_{ij}v_j(t)\bar{f}_j(u_j(t) - \tau_j)) \\
&\quad + \sum_{j=1}^{\infty} c_{ij}\int_{-\infty}^{\infty} K_{ij}(t-s)\bar{f}_j(u_j(s))ds.
\end{aligned}
\]

We consider the Lyapunov functional:
\[
V(t) = \sum_{i=1}^{n} \left( \frac{u_i^2(t) + v_i^2(t)}{2} \right) e^{\nu t}
\]

for \( i = 1, 2, \ldots, n. \)
\[ V(t) \geq \sum_{i=1}^{n} \frac{\varepsilon^2}{2} (|x_i - x^*_i|^2 + (y_i - y^*_i)^2). \]
\[
\frac{d^2 x_i(t)}{dt^2} = -\beta_i \frac{dx_i(t)}{dt} - \alpha_i x_i(t) \\
+ \sum_{j=1}^{2} a_{ij} f_j(x_j(t)) + \sum_{j=1}^{2} b_{ij} f_j(x_j(t) - \tau_{ij}) \\
+ \sum_{j=1}^{2} c_{ij} \int_{-\infty}^{t} K_{ij}(t-s) f_j(x_j(s)) ds + I_i(t),
\]
for \(i = 1, 2\), where \(\alpha_1 = 2, \alpha_2 = 3, \beta_1 = 3, \beta_2 = 4\),

\[
a_{11} = \frac{1}{32}, \quad a_{12} = \frac{1}{64}, \quad a_{21} = -\frac{1}{32}, \quad a_{22} = -\frac{1}{64}
\]

\[
b_{11} = -\frac{1}{32}, \quad b_{12} = \frac{1}{64}, \quad b_{21} = \frac{1}{32}, \quad b_{22} = -\frac{1}{64}
\]

\[
c_{11} = \frac{1}{64}, \quad c_{12} = \frac{1}{32}, \quad c_{21} = -\frac{1}{64}, \quad c_{22} = \frac{1}{32}
\]

\[
f_i(x) = \frac{1}{8} \sin(8x), \quad K_{ij}(x) = e^{-x}, \quad I_i(t) = \frac{1}{4} \cos(8t),
\]
for \(i = 1, 2\).

Obviously,

\[
|f_i(x) - f_i(y)| \leq |x - y|, \quad i = 1, 2,
\]

\[
\int_{0}^{+\infty} K_{ij}(s) ds = \int_{0}^{+\infty} e^{-s} ds = 1, \quad i, j = 1, 2,
\]

\[I_i = 1/4, \quad i = 1, 2\]

We select \(L_i = 1, \bar{f}_i = 1/8, \bar{I}_i = 1/4(i = 1, 2), \omega = \pi/4\), hypotheses (H1) - (H2) are hold.

For numerical simulation, let \(\tau_{11} = 0.2, \tau_{12} = 0.3, \tau_{21} = 0.1, \tau_{22} = 0.4\), the following four cases are given:

- **Case 1** with the initial state
  \([\varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0)] = [0.3, 0.2, 1.5, 2, 3]\)

- **Case 2** with the initial state
  \([\varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0)] = [0.25, 0.25, 1.1, 2.2]\)

- **Case 3** with the initial state
  \([\varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0)] = [0.4, 0.1, 1.15, 2.24]\)

- **Case 4** with the initial state
  \([\varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0)] = [0.5, 0.3, 1.28, 2.35]\)

Figs. 1-2 depict the time responses of state variables of system in example 4.1, respectively.

On the other hand, by calculation, we have the following results

\[
\beta_1^2 - 4\alpha_1 = 1 > 0, \quad \beta_2^2 - 4\alpha_2 = 4 > 0, \quad \psi_i(0) > 0, \quad i = 1, 2.
\]

\[
d_1 = \sum_{j=1}^{2} f_j[|a_{1j}| + |b_{1j}| + |c_{1j}|] + I_1 = \frac{137}{372}.
\]

\[
d_2 = \sum_{j=1}^{2} f_j[|a_{2j}| + |b_{2j}| + |c_{2j}|] + I_2 = \frac{137}{372}.
\]

\[
e = \min_{1 \leq i \leq 2} \{d_i\} = \frac{137}{372},
\]

\[
\varphi_1(0) > \frac{e}{\alpha_1} = \frac{137}{1566} \approx 0.089.
\]

Since \(\beta_1^2 - 4\alpha_1 > 0(i = 1, 2)\). By Lemma 4 we have

\[
\mu_1 = \frac{1}{2}[|\beta_1| + \sqrt{|\beta_1^2 - 4\alpha_1|}] = 2,
\]

\[
\mu_2 = \frac{1}{2}[|\beta_2| + \sqrt{|\beta_2^2 - 4\alpha_2|}] = 3,
\]

\[
M_1 = \frac{1}{2}(|\beta_1 - \alpha_1|^2 + 2|\beta_1 - 2\alpha_1|) = 2,
\]

\[
M_2 = \frac{2(|\beta_2 - 2\alpha_2|^2 + 2|\beta_2 - 2\alpha_2|) = \frac{\sqrt{170}}{2}.
\]

\[
N_1 = \frac{1}{|\beta_1^2 - 4\alpha_1|^2} e^{-\frac{\alpha}{2}} \left(e^{-\frac{\beta_1}{2}} - e^{-\frac{\beta_1^2 - 4\alpha_1}{2}} + e^{-\frac{\beta_2}{2}} - e^{-\frac{\beta_2^2 - 4\alpha_2}{2}} \right) + 1
\]
Obviously, 
\[ \begin{align*}
\beta_1 & = \frac{1}{4}, \quad \alpha_2 = \frac{2}{5}, \quad \beta_2 = 2, \quad \beta_2 = 3, \\
& \quad \bullet f_1(x) = \frac{1}{128}\sin(8x), \quad I_1(t) = \frac{1}{64}\cos(8t), \quad i = 1, 2, \\
& \quad \text{the other parameters are the same as that in Example 4.1.} \\
& \quad \text{Obviously,} \\
& \quad |f_1(x) - f_1(y)| \leq \frac{1}{16}|x - y|, \quad I_1 = \frac{1}{64}, \quad i = 1, 2. \\
\end{align*} \]

We select \[ L_1 = \frac{1}{12}, \quad \bar{L}_1 = \frac{1}{128}, \quad \bar{I}_1 = \frac{1}{64}(i = 1, 2), \omega = \frac{\pi}{4}, \]

hypotheses (H1) - (H2) are hold.

For numerical simulation, let \( \tau_1 = 0.02, \tau_2 = 0.03, \tau_2 = 0.1, \tau_2 = 0.2, \) the following four cases are given:

\[
\begin{align*}
\text{case 1 with the initial state} & \quad \varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0) = [0.3; 0.7; 1.2; 2.1]; \\
\text{case 2 with the initial state} & \quad \varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0) = [0.1; 0.5; 1.1; 2.2]; \\
\text{case 3 with the initial state} & \quad \varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0) = [0.4, 0.1, 1.15, 2.24]; \\
\text{case 4 with the initial state} & \quad \varphi_1(0), \varphi_2(0), \psi_1(0), \psi_2(0) = [0.5, 0.3; 1.2; 2.3]. \\
\end{align*}
\]

Figs. 3-4 depict the time responses of state variables of \( x_1(t) \) and \( x_2(t) \) of system example 4.2, respectively.

On the other hand, by calculation, we have the following results
\[
\beta_1^2 - 4\alpha_1 = -1 < 0, \quad \beta_2^2 - 4\alpha_2 = -1 < 0, \quad \psi_1(0) > 0, \quad i = 1, 2. \\
\]

\[
\begin{align*}
& \quad d_1 = \sum_{j=1}^{2} \delta_j [a_{ij} + |b_{ij} + |c_{ij}|] + \bar{I}_i = \frac{137}{64} \\
& \quad d_2 = \sum_{j=1}^{2} \delta_j [a_{ij} + |b_{ij} + |c_{ij}|] + \bar{I}_i = \frac{137}{64} \\
& \quad e = \sum_{j=1}^{2} \delta_j (d_j) = \frac{137}{64} \\
& \quad \varphi_1(0) > \frac{3}{10} \approx 0.30, \quad \varphi_2(0) > \frac{3}{10} \approx 0.069. \\
\end{align*}
\]

Since \( \beta_1^2 - 4\alpha_1 < 0 \) (i = 1, 2). By Lemma 4 we have
\[
\begin{align*}
& \quad \mu_1 = \frac{1}{2} \beta_1 = 1, \\
& \quad \mu_2 = \frac{1}{2} \beta_2 = \frac{1}{2}, \\
& \quad M_1 = 2\left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2, \\
& \quad M_2 = 2\left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2. \\
\end{align*}
\]

\[
\begin{align*}
& \quad N_1 = \frac{1}{2} \left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2, \\
& \quad N_2 = \frac{1}{2} \left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2. \\
& \quad d_1 = \sum_{j=1}^{2} \delta_j [a_{ij} + |b_{ij} + |c_{ij}|] + \bar{I}_i = \frac{137}{64} \\
& \quad d_2 = \sum_{j=1}^{2} \delta_j [a_{ij} + |b_{ij} + |c_{ij}|] + \bar{I}_i = \frac{137}{64} \\
& \quad e = \sum_{j=1}^{2} \delta_j (d_j) = \frac{137}{64} \\
& \quad \varphi_1(0) > \frac{3}{10} \approx 0.30, \quad \varphi_2(0) > \frac{3}{10} \approx 0.069. \\
\end{align*}
\]

Since \( \beta_1^2 - 4\alpha_1 < 0 \) (i = 1, 2). By Lemma 4 we have
\[
\begin{align*}
& \quad \mu_1 = \frac{1}{2} \beta_1 = 1, \\
& \quad \mu_2 = \frac{1}{2} \beta_2 = \frac{1}{2}, \\
& \quad M_1 = 2\left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2, \\
& \quad M_2 = 2\left[\frac{(\alpha_1 + \alpha_2) + (1 + \beta_1 + \beta_2)}{4}\right]^2 < 2. \\
\end{align*}
\]
the system (18) has one \( \pi/4 \)- periodic solution, and all other solutions of system exponentially converge to it as \( t \to +\infty \). Evidently, this consequence is coincident with the results of numerical simulation.

V. CONCLUSIONS

Since the periodic solutions for system is very important in theories and applications. In this paper, we give theorems to ensure the existence and the exponential stability of the periodic solution for inertial neural networks with unbounded delay. Novel existence and stability conditions are stated in simple algebraic forms and their verification and applications are straightforward and convenient.

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REFERENCES


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