http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 10 (11): 2202-2207, 2011
ISSN 1812-5638 / DOI: 10.3923/itj.2011.2202.2207

Novel Robust Stability Criteria for a Class of Neural Networks with Mixed Time-varying Delays and Nonlinear Perturbations

[1]Guoquan Liu, [2]Simon X. Yang, [3]Yi Chai and [1]Wei Fu
[1]College of Automation, Chongqing University, Chongqing 400044, China
[2]School of Engineering, University of Guelph, Guelph, Ontario, (N1G2W1), Canada
[3]State Key Laboratory of Power Transmission Equipment and System Security and New Technology of Engineering, Chongqing University, Chongqing 400044, China

Abstract: The problem of robust stability for a class of neural networks with mixed time-varying delays and nonlinear perturbations is investigated. The mixed delays contain discrete and neutral-type time-varying delays. By constructing a general form of Lyapunov-Krasovskii functional, using some free-weighting matrices, two delay-dependent stability criteria are derived. In particular, the proposed stability conditions are presented in terms of LMI which can be easily solved by some standard numerical packages. In addition, the nonlinear perturbations (or norm-bounded uncertainty) which are more general than those discussed in the previous literature.

Key words: Robust stability, neural networks, linear matrix inequality (LMI), nonlinear perturbations, time-varying delays, norm-bounded uncertainty

INTRODUCTION

In the past several decades, artificial neural networks have been widely investigated and employed to solve many practical engineering problems in various fields. In the implementation of networks, time delay is often encountered and its existence is frequently a source of oscillations, chaos and instability (Liao *et al*., 2002; Cao and Wang, 2003, 2005). Thus, the stability analysis of various delayed neural networks models has been discussed by many authors and some stability criteria have been deduced (Li *et al*., 2007; Zhang *et al*., 2007; Zhang and Chen, 2008; Xiong and Xu, 2008; Yang *et al*., 2009). Recently, the stability of neural networks with neutral-type delays also has been deeply studied via the LMI technique and Lyapunov functions and several important stability conditions have been introduced, see (Qiu and Ren, 2006; Park *et al*., 2008; Lee *et al*., 2010) and their references.

On the other hand, the nonlinearities are the important sources of delayed system instability. Therefore, it is of great importance to consider nonlinear perturbations on the stability of delayed system (or neural network with time delays), (Xie *et al*., 2006; Wang *et al*., 2009; Kwon *et al*., 2008; Qiu *et al*., 2010). Based on the Lyapunov method, a sufficient delay-dependent criterion for asymptotic stability of dynamic systems with time-varying delays and nonlinear perturbations is derived by Kwon *et al*. (2008). However, neutral-type delays were not considered by Kwon *et al*. (2008). Using the Lyapunov functional technique combined with matrix inequality technique, Qiu *et al*. (2010) present a novel asymptotic stability criterion for neutral systems with nonlinear perturbations. Very recently, the stability of neural networks with norm-bounded uncertainties and neutral-type delays has received much attention (Lien *et al*., 2008; Zhu *et al*., 2009; Zhang *et al*., 2010). For example, Zhu *et al*. (2009) have investigated the stability analysis of neutral-type neural networks with parameter uncertainties via LMI approach. In Zhang *et al*. (2010), the robust stability of neural networks with neutral-type delays and parameter uncertainties is studied by employing a Lyapunov-Krasovskii functional combined with the LMI approach. Most of the obtained results are based on restricting norm-bounded for parameter uncertainty. However, to the best of the authors' knowledge, the robust stability analysis for a class of neural networks with nonlinear perturbations, discrete and neutral-type and time-varying delays has not been investigated which motives our research.

Present study is concerned with the robust stability analysis problem for a class of neural networks with both nonlinear perturbations and mixed time-varying delays, which comprise discrete, time-varying and neutral-type time delays. Based on the Lyapunov stability theory and

Corresponding Author: Guoquan Liu, College of Automation, Chongqing University, Chongqing 400044, P.R. China
Tel: 86013618395665

the free-weighting technique, the stability conditions are obtained in terms of LMI. In addition, the proposed stability conditions are delay-dependent. The proposed model of neural networks is quite general since many factors such as nonlinear perturbations, discrete time-varying delays and neutral-type time-varying delays are considered in this study.

Notations: Throughout this study, for symmetric matrices A and B, A > B (respectively, A≥B) means that A-B≥0 (A-B>0) is a positive semi-definite (respectively, positive definite) matrix. The superscripts T and -1 stand for matrix transposition and matrix inverse, respectively; $\Re_n$ and $\Re^{n\times n}$ denote the n-dimensional Euclidean space and the set of all n×n real matrices, respectively; *represents the blocks that are readily inferred by symmetry; {...} denotes the block diagonal matrix.

PROBLEM DESCRIPTION AND PRELIMINARIES

Consider the following a class of neural networks with mixed time-varying delays and nonlinear perturbations:

$$\begin{cases} \dot{x}(t) = -Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t)) + D\dot{x}(t-h(t)) \\ +f_1(t,x(t)) + f_2(t,f(x(t))) + f_3(t,f(x(t-\tau(t)))) + f_4(t,\dot{x}(t-h(t))), \\ x(\theta) = \vartheta(\theta), \dot{x}(\theta) = \delta(\theta), \forall\theta\in[-\max(h,\tau),0] \end{cases} \quad (1)$$

where, x (t) $\in\Re^n$ is the state vector, A$\in\Re^{n\times n}$, B$\in\Re^{n\times n}$, C$\in\Re^{n\times n}$ and C$\in\Re^{n\times n}$, are constant matrices. τ (t) and h (t) are time-varying discrete delay and neutral delay, respectively and they are assumed to satisfy:

$$0 \le \tau(t) \le \tau, \quad \dot{\tau}(t) \le \tau_d < 1, 0 \le h(t) \le h, \quad \dot{h}(t) \le h_d < 1 \quad (2)$$

where, τ, τ_d, h, h_d are constants, $\vartheta(\theta), \delta(\theta)$ are the initial condition functions that are continuously differentiable on [−max (h, τ), 0] $f_1(t,x(t)), f_2(t,f(x(t))), f_3(t,f(x(t-\tau(t))))$ and $f_4(t,\dot{x}(t-h(t)))$ are unknown nonlinear perturbations. They satisfy that f_i (t, 0) = 0, I = 1, 2, 3, 4:

$$\begin{aligned} &\|f_1(t,x(t))\| \le \alpha\|x(t)\|, \|f_2(t,f(x(t)))\| \le \beta\|f(x(t))\|, \\ &\|f_3(t,f(x(t-\tau(t)))\| \le \gamma f(x(t-\tau(t))), \|f_4(t,\dot{x}(t-h(t)))\| \le \pi\|\dot{x}(t-h(t))\| \end{aligned} \quad (3)$$

where, α ≥ 0,β ≥ 0,γ≥0 and π≥0 are given constants.

Eq. 3 can be rewritten as follow:

$$\begin{aligned} &f_1^T(t,x(t))f_1(t,x(t)) \le \alpha^2 x^T(t)x(t), f_2^T(t,f(x(t)))f_2(t,f(x(t))) \le \beta^2 f^T(x(t))f(x(t)), \\ &f_3^T(t,f(x(t-\tau(t))))f_3(t,f(x(t-\tau(t)))) \le \gamma^2 f^T(x(t-\tau(t)))f(x(t-\tau(t))), \\ &f_4^T(t,\dot{x}(t-h(t)))f_4(t,\dot{x}(t-h(t))) \le \pi^2 \dot{x}^T(t-h(t))\dot{x}(t-h(t)) \end{aligned} \quad (4)$$

For the sake of simplicity, the following notations are adopted:

$$f_1 := f_1(t,x(t)), f_2 := f_2(t,f(x(t))), f_3 := f(t,x(t-\tau(t))), f_4 := f(t,\dot{x}(t-h(t)))$$

Then, system (1) can be rewritten as:

$$\dot{x}(t) = -Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t)) + D\dot{x}(t-h(t)) + f_1 + f_2 + f_3 + f_4 \quad (5)$$

The following lemmas will be used in the development of main results in sequel.

Lemma 1(Schur complement): Given constant S_1, S_2 and S_3 with appropriate dimensions where, $S^T_1 = S_1$ and $S_2^T = S_2 > 0$ then $S_1 + S_3^T S_2^{-1} S_3 < 0$ if and only if:

$$\begin{bmatrix} S_1 & S_3^T \\ * & -S_2 \end{bmatrix} < 0 \text{ or } \begin{bmatrix} -S_2 & S_3 \\ * & S_1 \end{bmatrix} < 0 \quad (6)$$

Lemma 2: For any constant matrix M$\in\Re^{n\times n}$, M = M^T > 0 scalars a, b satisfying a<b and vector function ω: [a, b] →$\Re^n$ such that the integrations concerned are well defined, then:

$$\left(\int_a^b \omega(s)ds\right)^T M\left(\int_a^b \omega(s)ds\right) \le (b-a)\int_a^b \omega^T(s)M\omega(s)ds \quad (7)$$

Lemma 3: Letandbe real constant matrices with appropriate dimensions, matrix F (t) satisfies F^T (t) F (t) ≤I. Then we have:

$$\begin{aligned} &(1) \quad \text{For any } p>0,\ 2A^TD \le A^TPA + D^TP^{-1}D, \\ &(2) \quad \text{For any } \varepsilon>0,\ DF(t)E + E^TF^T(t)D^T \le \varepsilon^{-1}DD^T + \varepsilon E^TE \end{aligned} \quad (8)$$

MAIN RESULTS

The main results of this study are given in the following theorems.

New stability criterion

Theorem 1: Assume time-varying delays τ (t) and h (t) satisfy (2), system (1) is robustly stable, if there exist matrices:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ * & P_{22} \end{bmatrix} > 0, Q = \begin{bmatrix} Q_{11} & Q_{12} \\ * & Q_{22} \end{bmatrix} > 0, R = \begin{bmatrix} R_{11} & R_{12} \\ * & R_{22} \end{bmatrix} > 0, Z = \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22} \end{bmatrix} > 0,$$
$$E_i > 0, i = 1,2$$

N_i, M_i, K_i, i = 1, 2, ..., 12 and positive scalars ε_i > 0, i = 1, 2, 3, 4 such that the following LMI hold:

$$\Pi = \begin{bmatrix} \Pi_1 & N & M \\ * & -E_1 & 0 \\ * & * & -E_2 \end{bmatrix} < 0 \quad (9)$$

where,

$$\Pi_1 = \Pi_1^T = \left[\varphi_{i,j}\right]_{12\times 12}, i, j = 1, 2, ..., 12, M^T = \left[M_i\right]_{1\times 12},$$
$$N^T = \left[N_i\right]_{1\times 12}, i = 1, 2, ..., 12$$

with:

$$\varphi_{1,1} = Q_{11} + R_{11} + Z_{11} + \varepsilon_1\alpha^2 I + N_1 + N_1^T + M_1 + M_1^T - K_1A - A^T K_1^T,$$
$$\varphi_{1,2} = Q_{12} + R_{12} + N_2^T + M_2^T - A^T K_2^T + K_1B, \varphi_{1,3} = N_3^T + M_3^T - A^T K_3^T + K_1C,$$
$$\varphi_{1,4} = N_4^T - N_1 + M_4^T - A^T K_4^T, \varphi_{1,5} = N_5^T + M_5^T - M_1 - A^T K_5^T, \varphi_{1,6} = N_6^T + M_6^T - A^T K_6^T,$$
$$\varphi_{1,7} = N_7^T + M_7^T - A^T K_7^T + K_1D, \varphi_{1,8} = P_{11} + P_{12} + Z_{12} + N_8^T + M_8^T - A^T K_8^T - K_1,$$
$$\varphi_{1,9} = N_9^T + M_9^T - A^T K_9^T + K_1, \varphi_{1,10} = N_{10}^T + M_{10}^T - A^T K_{10}^T + K_1, \varphi_{1,11} = N_{11}^T + M_{11}^T - A^T K_{11}^T + K_1,$$
$$\varphi_{1,12} = N_{12}^T + M_{12}^T - A^T K_{12}^T + K_1, \varphi_{2,2} = Q_{22} + R_{22} + \varepsilon_2\beta^2 I + K_2B + B^T K_2^T, \varphi_{2,3} = B^T K_3^T + K_2C,$$
$$\varphi_{2,4} = -N_2 + B^T K_4^T, \varphi_{2,5} = -M_2 + B^T K_5^T, \varphi_{2,6} = B^T K_6^T, \varphi_{2,7} = B^T K_7^T + K_2D, \varphi_{2,8} = B^T K_8^T - K_2,$$
$$\varphi_{2,9} = B^T K_9^T + K_2, \varphi_{2,10} = B^T K_{10}^T + K_2, \varphi_{2,11} = B^T K_{11}^T + K_2, \varphi_{2,12} = B^T K_{12}^T + K_2,$$
$$\varphi_{3,3} = -(1-\tau_d)Q_{22} + \varepsilon_3\gamma^2 I + K_3C + C^T K_3^T, \varphi_{3,4} = -(1-\tau_d)Q_{12}^T - N_3 + C^T K_4^T,$$
$$\varphi_{3,5} = -M_3 + C^T K_5^T, \varphi_{3,6} = C^T K_6^T, \varphi_{3,7} = C^T K_7^T + K_3D, \varphi_{3,8} = C^T K_8^T - K_3,$$
$$\varphi_{3,9} = C^T K_9^T + K_3, \varphi_{3,10} = C^T K_{10}^T + K_3, \varphi_{3,11} = C^T K_{11}^T + K_3, \varphi_{3,12} = C^T K_{12}^T + K_3,$$
$$\varphi_{4,4} = -(1-\tau_d)Q_{11} - N_4 - N_4^T, \varphi_{4,5} = -N_5^T - M_4, \varphi_{4,6} = -N_6^T, \varphi_{4,7} = -N_7^T + K_4D,$$
$$\varphi_{4,8} = -N_8^T - K_4, \varphi_{4,9} = -N_9^T + K_4, \varphi_{4,10} = -N_{10}^T + K_4, \varphi_{4,11} = -N_{11}^T + K_4, \varphi_{4,12} = -N_{12}^T + K_4,$$
$$\varphi_{5,5} = -(1-h_d)R_{11} - (1-h_d)Z_{11} - M_5 - M_5^T, \varphi_{5,6} = -(1-h_d)R_{12} - M_6^T,$$
$$\varphi_{5,7} = P_{22} - (1-h_d)Z_{12} - M_7^T + K_5D, \varphi_{5,8} = P_{12}^T - M_8^T - K_5, \varphi_{5,9} = -M_9^T + K_5, \varphi_{5,10} = -M_{10}^T + K_5,$$
$$\varphi_{5,11} = -M_{11}^T + K_5, \varphi_{5,12} = -M_{12}^T + K_5, \varphi_{6,6} = -(1-h_d)R_{22}, \varphi_{6,7} = K_7D, \varphi_{6,8} = -K_6, \varphi_{6,9} = K_6, \varphi_{6,10} = K_6,$$
$$\varphi_{6,11} = K_6, \varphi_{6,12} = K_6, \varphi_{7,7} = -(1-h_d)Z_{22} + \varepsilon_4\pi^2 I + K_7D + D^T K_7^T,$$
$$\varphi_{7,8} = D^T K_8^T - K_7, \varphi_{7,9} = D^T K_9^T + K_7, \varphi_{7,10} = D^T K_{10}^T + K_7, \varphi_{7,11} = D^T K_{11}^T + K_7,$$
$$\varphi_{7,12} = D^T K_{12}^T + K_7, \varphi_{8,8} = Z_{22} - K_8 - K_8^T + \tau^2 E_1 + h^2 E_2, \varphi_{8,9} = -K_9^T + K_8, \varphi_{8,10} = -K_{10}^T + K_8,$$
$$\varphi_{8,11} = -K_{11}^T + K_8, \varphi_{8,12} = -K_{12}^T + K_8, \varphi_{9,9} = -\varepsilon_1 I + K_9 + K_9^T, \varphi_{9,10} = K_{10}^T + K_9,$$
$$\varphi_{9,11} = K_{11}^T + K_9, \varphi_{9,12} = K_{12}^T + K_9, \varphi_{10,10} = -\varepsilon_2 I + K_{10} + K_{10}^T, \varphi_{10,11} = K_{10}, \varphi_{10,12} = K_{10},$$
$$\varphi_{11,11} = -\varepsilon_3 I + K_{11} + K_{11}^T, \varphi_{11,12} = K_{12}^T + K_{11}, \varphi_{12,12} = -\varepsilon_4 I + K_{12} + K_{12}^T$$

Proof: First, Let us introduce the lyapunov-krasoskill functional as follows:

$$V(x(t)) = V_1(x(t)) + V_2(x(t)) + V_3(x(t)) + V_4(x(t)) + V_5(x(t)) \quad (10)$$

where,

$$V_1(x(t),t) = \begin{bmatrix} x(t) \\ x(t-h(t)) \end{bmatrix}^T P \begin{bmatrix} x(t) \\ x(t-h(t)) \end{bmatrix}, V_2(x(t),t) = \int_{t-\tau(t)}^{t} \begin{bmatrix} x(s) \\ f(x(s)) \end{bmatrix}^T Q \begin{bmatrix} x(s) \\ f(x(s)) \end{bmatrix} ds,$$
$$V_3(x(t),t) = \int_{t-h(t)}^{t} \begin{bmatrix} x(s) \\ f(x(s)) \end{bmatrix}^T R \begin{bmatrix} x(s) \\ f(x(s)) \end{bmatrix} ds, V_4(x(t),t) = \int_{t-h(t)}^{t} \begin{bmatrix} x(s) \\ \dot{x}(s) \end{bmatrix}^T Z \begin{bmatrix} x(s) \\ \dot{x}(s) \end{bmatrix} ds,$$
$$V_5(x(t),t) = \tau\int_{t-\tau}^{t}\int_{\theta}^{t} \dot{x}^T(s)E_1\dot{x}(s)ds d\theta + h\int_{t-h}^{t}\int_{\theta}^{t} \dot{x}^T(s)E_2\dot{x}(s)ds d\theta \quad (11)$$

The time derivative ofalong the trajectory of system (1) is given by:

$$\dot{V}(x(t)) = \dot{V}_1(x(t)) + \dot{V}_2(x(t)) + \dot{V}_3(x(t)) + \dot{V}_4(x(t)) + \dot{V}_5(x(t)) \quad (12)$$

where,

$$\dot{V}_1(x(t),t) = 2\begin{bmatrix} x(t) \\ x(t-h(t)) \end{bmatrix}^T P \begin{bmatrix} \dot{x}(t) \\ \dot{x}(t-h(t)) \end{bmatrix} = 2\begin{bmatrix} x(t) \\ x(t-h(t)) \end{bmatrix}^T \begin{bmatrix} P_{11} & P_{12} \\ * & P_{22} \end{bmatrix} \begin{bmatrix} \dot{x}(t) \\ \dot{x}(t-h(t)) \end{bmatrix}$$
$$= 2x^T(t)P_{11}\dot{x}(t) + 2x^T(t-h(t))P_{12}^T\dot{x}(t) + 2x^T(t)P_{12}\dot{x}(t) + 2x^T(t-h(t))P_{22}\dot{x}(t-h(t)) \quad (13)$$

$$\dot{V}_2(x(t),t) \le \begin{bmatrix} x(t) \\ f(x(t)) \end{bmatrix}^T Q \begin{bmatrix} x(t) \\ f(x(t)) \end{bmatrix} - (1-\tau_d)\begin{bmatrix} x(t-\tau(t)) \\ f(x(t-\tau(t))) \end{bmatrix}^T Q \begin{bmatrix} x(t-\tau(t)) \\ f(x(t-\tau(t))) \end{bmatrix} \quad (14)$$

$$\dot{V}_3(x(t),t) \le \begin{bmatrix} x(t) \\ f(x(t)) \end{bmatrix}^T R \begin{bmatrix} x(t) \\ f(x(t)) \end{bmatrix} - (1-h_d)\begin{bmatrix} x(t-h(t)) \\ f(x(t-h(t))) \end{bmatrix}^T R \begin{bmatrix} x(t-h(t)) \\ f(x(t-h(t))) \end{bmatrix} \quad (15)$$

$$\dot{V}_4(x(t),t) \le \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}^T Z \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix} - (1-h_d)\begin{bmatrix} x(t-h(t)) \\ \dot{x}(t-h(t)) \end{bmatrix}^T \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22} \end{bmatrix} \begin{bmatrix} x(t-h(t)) \\ \dot{x}(t-h(t)) \end{bmatrix} \quad (16)$$

$$\dot{V}_5(x(t),t) = \tau^2\dot{x}^T(t)E_1\dot{x}(t) - \tau\int_{t-\tau}^{t}\dot{x}^T(s)E_1\dot{x}(s)ds + h^2\dot{x}^T(t)E_2\dot{x}(t) - h\int_{t-h}^{t}\dot{x}^T(s)E_2\dot{x}(s)ds \quad (17)$$

By applying Lemma 2, it follows that:

$$-\tau\int_{t-\tau}^{t}\dot{x}^T(s)E_1\dot{x}(s)ds \le -\left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right]^T E_1\left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right],$$
$$-h\int_{t-h}^{t}\dot{x}^T(s)E_2\dot{x}(s)ds \le -\left[\int_{t-h(t)}^{t}\dot{x}(s)ds\right]^T E_2\left[\int_{t-h(t)}^{t}\dot{x}(s)ds\right] \quad (18)$$

By using the Newton-Leibniz formula and Eq. 5, one has:

$$2\xi^T(t)N\left[x(t) - x(t-\tau(t)) - \int_{t-\tau(t)}^{t}\dot{x}(s)ds\right] = 0 \quad (19)$$

$$2\xi^T(t)M\left[x(t) - x(t-h(t)) - \int_{t-h(t)}^{t}\dot{x}(s)ds\right] = 0 \quad (20)$$

$$2\xi^T(t)K\begin{bmatrix} -Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t)) + \\ D\dot{x}(t-h(t)) + f_1 + f_2 + f_3 + f_4 - \dot{x}(t) = 0 \end{bmatrix} \quad (21)$$

By applying Lemma 3, it follows that:

$$-2\xi^T(t)N\int_{t-\tau(t)}^{t}\dot{x}(s)ds \le \xi^T(t)NE_1^{-1}N^T\xi(t) + \left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right]^T E_1\left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right],$$
$$-2\xi^T(t)M\int_{t-\tau(t)}^{t}\dot{x}(s)ds \le \xi^T(t)ME_2^{-1}M^T\xi(t) + \left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right]^T E_2\left[\int_{t-\tau(t)}^{t}\dot{x}(s)ds\right] \quad (22)$$

From Eq. 3, one can obtain for any scalars $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, $\varepsilon_3 > 0$ and $\varepsilon_4 > 0$:

$$\varepsilon_1\left[\alpha^2 x^T(t)x(t) - f_1^Tf_1\right] \ge 0, \ \varepsilon_2\left[\beta^2 f^T(x(t))f(x(t)) - f_2^Tf_2\right] \ge 0,$$
$$\varepsilon_3\left[\gamma^2 f^T(x(t-\tau(t)))f(x(t-\tau(t))) - f_3^Tf_3\right] \ge 0, \varepsilon_4\left[\pi^2\dot{x}^T(t-h(t))\dot{x}(t-h(t)) - f_4^Tf_4\right] \ge 0 \quad (23)$$

Combining Eq. 13-23, it is easy to verify that:

$$\dot{V}(x(t)) \le \xi^T(t)\,\Pi\,\xi(t) \tag{24}$$

where,

$$\xi^T(t) = \begin{bmatrix} x^T(t), f^T(x(t)), f^T(x-\tau(t)), x^T(t-\tau(t)), x^T(t-h(t)), \\ f^T(x-h(t)), \dot{x}^T(t-h(t)), \dot{x}^T(t), f_1^T, f_2^T, f_3^T, f_4^T \end{bmatrix}$$

It is obvious that for $\Pi < 0$, by using the Lyapunov-Krasovskii stability theorem, one can conclude that the neural network of neutral-type (1) is globally asymptotically stable if (9) holds. This completes the proof of Theorem 1.

Norm-bounded uncertainty: Here, we will present a delay-dependent robust criterion for the system (1) that $f_1(t,x(t)), f_2(t,f(x(t))), f_3(t,f(x(t-\tau(t))))$ and $f_4(t,\dot{x}(t-h(t)))$ are norm-bounded uncertainties. That is:

$$\begin{aligned} & f_1(t,x(t)) = \Delta A(t)\,x(t), f_2(t,f(x(t))) = \Delta B(t)\,f(x(t)), \\ & f_3(t,f(x(t-\tau(t)))) = \Delta C(t)\,f(x(t-\tau(t))), \\ & f_3(t,\dot{x}(t-h(t))) = \Delta D(t)\dot{x}(t-h(t)) \end{aligned} \tag{25}$$

The time-varying uncertainties are of the form:

$$[\Delta A(t) \quad \Delta B(t) \quad \Delta C(t) \quad \Delta D(t)] = LF(t)[T_1 \quad T_2 \quad T_3 \quad T_4] \tag{26}$$

where, T_i, i = 1, 2, 3, 4, L are constant matrices of appropriate dimensions. F (t) is an unknown and possibly time-varying real matrix with Lebesgue measurable elements and satisfies:

$$F^T(t)\,F(t) \le I, \quad \forall t \in \Re \tag{27}$$

Then, system (1) becomes the following system:

$$\begin{cases} \dot{x}(t) = -(A+\Delta A(t))\,x(t) + (B+\Delta B(t))\,f(x(t)) + (C+\Delta C(t))\,f(x(t-\tau(t))) + \\ (D+\Delta D(t))\,\dot{x}(t-h(t)),\ x(\theta) = \vartheta(\theta), \dot{x}(\theta) = \delta(\theta), \forall \theta \in [-\max(h,\tau), 0] \end{cases} \tag{28}$$

Theorem 2: Assume time-varying delays τ (t) and h (t) satisfy (2), system (28) is robustly stable, if there exist matrices:

$$P = \begin{bmatrix} P_{11} & P_{12} \\ * & P_{22} \end{bmatrix} > 0, Q = \begin{bmatrix} Q_{11} & Q_{12} \\ * & Q_{22} \end{bmatrix} > 0, R = \begin{bmatrix} R_{11} & R_{12} \\ * & R_{22} \end{bmatrix} > 0,$$

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22} \end{bmatrix} > 0, E_i > 0$$

i = 1, 2, N_i, M_i, K_i, I = 1, 2, ..., 12 and positive scalar ε > 0 such that the following LMI holds:

$$\begin{bmatrix} \bar{\Pi}_1 & \bar{N} & \bar{M} & \Gamma \\ * & -E_1 & 0 & 0 \\ * & * & -E_2 & 0 \\ * & * & * & -\varepsilon I \end{bmatrix} < 0 \tag{29}$$

where,

$$\bar{\Pi}_1 = \bar{\Pi}_1^T = [\bar{\varphi}_{i,j}]_{8\times 8}, i,j = 1,2,...,8, \bar{M}^T = [M_i]_{1\times 8}, i = 1,2...,8, \bar{N}^T = [N_i]_{1\times 8}, i = 1,2...,8, \Gamma = [K_i H]_{8\times 1}$$

with:

$$\begin{aligned}
&\bar{\varphi}_{1,1} = Q_{11} + R_{11} + Z_{11} + N_1 + N_1^T + M_1 + M_1^T - K_1 A - A^T K_1^T + \varepsilon T_1^T T_1, \\
&\bar{\varphi}_{1,2} = Q_{12} + R_{12} + N_2^T + M_2^T - A^T K_2^T + K_1 B, \bar{\varphi}_{1,3} = N_3^T + M_3^T - A^T K_3^T + K_1 C, \bar{\varphi}_{1,4} = N_4^T - N_1 + M_4^T - A^T K_4^T, \\
&\bar{\varphi}_{1,5} = N_5^T + M_5^T - M_1 - A^T K_5^T, \bar{\varphi}_{1,6} = N_6^T + M_6^T - A^T K_6^T, \bar{\varphi}_{1,7} = N_7^T + M_7^T - A^T K_7^T + K_1 D, \\
&\bar{\varphi}_{1,8} = P_{11} + P_{12} + Z_{12} + N_8^T + M_8^T - A^T K_8^T - K_1, \bar{\varphi}_{2,2} = Q_{22} + R_{22} + K_2 B + B^T K_2^T + \varepsilon T_2^T T_2, \bar{\varphi}_{2,3} = B^T K_3^T + K_2 C, \\
&\bar{\varphi}_{2,4} = -N_2 + B^T K_4^T, \bar{\varphi}_{2,5} = -M_2 + B^T K_5^T, \bar{\varphi}_{2,6} = B^T K_6^T, \bar{\varphi}_{2,7} = B^T K_7^T + K_2 D, \bar{\varphi}_{2,8} = B^T K_8^T - K_2, \\
&\bar{\varphi}_{3,5} = -M_3 + C^T K_5^T, \bar{\varphi}_{3,6} = C^T K_6^T +, \varphi_{3,7} = C^T K_7^T + K_3 D, \bar{\varphi}_{3,8} = C^T K_8^T - K_3, \bar{\varphi}_{4,4} = -(1-\tau_d)Q_{11} - N_4 - N_4^T, \\
&\bar{\varphi}_{4,5} = -N_5^T - M_4, \bar{\varphi}_{4,6} = -N_6^T, \bar{\varphi}_{3,3} = -(1-\tau_d)Q_{22} + K_3 C + C^T K_3^T + \varepsilon T_3^T T_3, \bar{\varphi}_{3,4} = -(1-\tau_d)Q_{12}^T - N_3 + C^T K_4^T, \\
&\bar{\varphi}_{4,7} = -N_7^T + K_4 D, \bar{\varphi}_{4,8} = -N_8^T - K_4, \bar{\varphi}_{5,5} = -(1-h_d)R_{11} - (1-h_d)Z_{11} - M_5 - M_5^T, \bar{\varphi}_{5,6} = -(1-h_d)R_{12} - M_6^T, \\
&\bar{\varphi}_{5,7} = P_{22} - (1-h_d)Z_{12} - M_7^T + K_5 D, \bar{\varphi}_{5,8} = P_{12}^T - M_8^T - K_5, \bar{\varphi}_{6,6} = -(1-h_d)R_{22}, \bar{\varphi}_{6,7} = K_7 D, \\
&\bar{\varphi}_{6,8} = -K_6, \bar{\varphi}_{7,7} = -(1-h_d)Z_{22} + K_7 D + D^T K_7^T + \varepsilon T_4^T T_4, \bar{\varphi}_{7,8} = D^T K_8^T - K_7, \bar{\varphi}_{8,8} = Z_{22} - K_8 - K_8^T + \tau^2 E_1 + h^2 E_2
\end{aligned}$$

Proof: Using Lemma 2(Schur complement),

$$\bar{\Pi} = \begin{bmatrix} \bar{\Pi}_1 & \bar{N} & \bar{M} \\ * & -E_1 & 0 \\ * & * & -E_2 \end{bmatrix} < 0$$

implies that:

$$\bar{\Pi} = \begin{bmatrix}
\tilde{\varphi}_{1,1} & \bar{\varphi}_{1,2} & \bar{\varphi}_{1,3} & \bar{\varphi}_{1,4} & \bar{\varphi}_{1,5} & \bar{\varphi}_{1,6} & \bar{\varphi}_{1,7} & \bar{\varphi}_{1,8} \\
* & \tilde{\varphi}_{2,2} & \bar{\varphi}_{2,3} & \bar{\varphi}_{2,4} & \bar{\varphi}_{2,5} & \bar{\varphi}_{2,6} & \bar{\varphi}_{2,7} & \bar{\varphi}_{2,8} \\
* & * & \tilde{\varphi}_{3,3} & \bar{\varphi}_{3,4} & \bar{\varphi}_{3,5} & \bar{\varphi}_{3,6} & \bar{\varphi}_{3,7} & \bar{\varphi}_{3,8} \\
* & * & * & \bar{\varphi}_{4,4} & \bar{\varphi}_{4,5} & \bar{\varphi}_{4,6} & \bar{\varphi}_{4,7} & \bar{\varphi}_{4,8} \\
* & * & * & * & \bar{\varphi}_{5,5} & \bar{\varphi}_{5,6} & \bar{\varphi}_{5,7} & \bar{\varphi}_{5,8} \\
* & * & * & * & * & \bar{\varphi}_{6,6} & \bar{\varphi}_{6,7} & \bar{\varphi}_{6,8} \\
* & * & * & * & * & * & \tilde{\varphi}_{7,7} & \bar{\varphi}_{7,8} \\
* & * & * & * & * & * & * & \bar{\varphi}_{8,8}
\end{bmatrix} + \varepsilon \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix} \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix}^T + \varepsilon^{-1} \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix} \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix}^T < 0 \tag{30}$$

where,

$$\begin{aligned}
&\tilde{\varphi}_{1,1} = Q_{11} + R_{11} + Z_{11} + N_1 + N_1^T + M_1 + M_1^T - K_1 A - A^T K_1^T, \\
&\tilde{\varphi}_{2,2} = Q_{22} + R_{22} + K_2 B + B^T K_2^T, \tilde{\varphi}_{3,3} = -(1-\tau_d)Q_{22} + K_3 C + C^T K_3^T, \\
&\tilde{\varphi}_{7,7} = -(1-h_d)Z_{22} + K_7 D + D^T K_7^T
\end{aligned}$$

Then, noting that Eq. 26 and 27, using Lemma 3, one has:

$$\begin{bmatrix} \Delta\bar{\varphi}_{1,1} & \Delta\bar{\varphi}_{1,2} & \Delta\bar{\varphi}_{1,3} & \Delta\bar{\varphi}_{1,4} & \Delta\bar{\varphi}_{1,5} & \Delta\bar{\varphi}_{1,6} & \Delta\bar{\varphi}_{1,7} & \Delta\bar{\varphi}_{1,8} \\ * & \Delta\bar{\varphi}_{2,2} & \Delta\bar{\varphi}_{2,3} & \Delta\bar{\varphi}_{2,4} & \bar{\varphi}_{2,5} & \Delta\bar{\varphi}_{2,6} & \Delta\bar{\varphi}_{2,7} & \Delta\bar{\varphi}_{2,8} \\ * & * & \Delta\bar{\varphi}_{3,3} & \Delta\bar{\varphi}_{3,4} & \Delta\bar{\varphi}_{3,5} & \Delta\bar{\varphi}_{3,6} & \Delta\bar{\varphi}_{3,7} & \Delta\bar{\varphi}_{3,8} \\ * & * & * & 0 & 0 & 0 & \Delta\bar{\varphi}_{4,7} & 0 \\ * & * & * & * & 0 & 0 & \Delta\bar{\varphi}_{5,7} & 0 \\ * & * & * & * & * & 0 & \Delta\bar{\varphi}_{6,7} & 0 \\ * & * & * & * & * & * & \Delta\bar{\varphi}_{7,7} & \Delta\bar{\varphi}_{7,8} \\ * & * & * & * & * & * & * & 0 \end{bmatrix}$$

$$= \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix} F^T(t) \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix}^T + \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix} F(t) \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix}^T \le \varepsilon \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix} \begin{bmatrix} -T_1^T \\ T_2^T \\ T_3^T \\ 0 \\ 0 \\ 0 \\ T_4^T \\ 0 \end{bmatrix}^T + \varepsilon^{-1} \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix} \begin{bmatrix} KH_1 \\ KH_2 \\ KH_3 \\ KH_4 \\ KH_5 \\ KH_6 \\ KH_7 \\ KH_8 \end{bmatrix}^T \quad (31)$$

Where:

$\Delta\bar{\varphi}_{1,1} = -K_1\Delta A(t) - \Delta A^T(t)K_1^T, \Delta\bar{\varphi}_{1,2} = -\Delta A^T(t)K_2^T, \Delta\bar{\varphi}_{1,3} = -\Delta A^T(t)K_3^T, \Delta\bar{\varphi}_{1,4} = -\Delta A^T(t)K_4^T,$
$\Delta\bar{\varphi}_{1,5} = -\Delta A^T(t)K_5^T, \Delta\bar{\varphi}_{1,6} = -\Delta A^T(t)K_6^T, \Delta\bar{\varphi}_{1,7} = -\Delta A^T(t)K_7^T + K_1\Delta D(t), \Delta\bar{\varphi}_{1,8} = -\Delta A^T(t)K_8^T,$
$\Delta\bar{\varphi}_{2,2} = K_2\Delta B(t) + \Delta B^T(t)K_2^T, \Delta\bar{\varphi}_{2,3} = \Delta B^T(t)K_3^T, \Delta\bar{\varphi}_{2,4} = \Delta B^T(t)K_4^T, \Delta\bar{\varphi}_{2,5} = \Delta B^T(t)K_5^T,$
$\Delta\bar{\varphi}_{2,6} = \Delta B^T(t)K_6^T, \Delta\bar{\varphi}_{2,7} = \Delta B^T(t)K_7^T + K_2D, \Delta\bar{\varphi}_{2,8} = \Delta B^T(t)K_8^T, \Delta\bar{\varphi}_{3,3} = K_3\Delta C(t) + \Delta C^T(t)K_3^T,$
$\Delta\bar{\varphi}_{3,4} = \Delta C^T(t)K_4^T, \Delta\bar{\varphi}_{3,5} = \Delta C^T(t)K_5^T, \bar{\varphi}_{3,6} = \Delta C^T(t)K_6^T, \Delta\bar{\varphi}_{3,7} = \Delta C^T(t)K_7^T, \bar{\varphi}_{3,8} = \Delta C^T(t)K_8^T,$
$\Delta\bar{\varphi}_{4,7} = K_4\Delta D(t), \Delta\bar{\varphi}_{5,7} = K_5\Delta D(t), \Delta\bar{\varphi}_{6,7} = K_7\Delta D(t), \Delta\bar{\varphi}_{7,7} = K_7\Delta D(t) + \Delta D^T(t)K_7^T, \Delta\bar{\varphi}_{7,8} = \Delta D^T(t)K_8^T$

Therefore, one obtains:

$$\hat{\Pi} = \begin{bmatrix} \hat{\varphi}_{1,1} & \hat{\varphi}_{1,2} & \hat{\varphi}_{1,3} & \hat{\varphi}_{1,4} & \hat{\varphi}_{1,5} & \hat{\varphi}_{1,6} & \hat{\varphi}_{1,7} & \hat{\varphi}_{1,8} \\ * & \hat{\varphi}_{2,2} & \hat{\varphi}_{2,3} & \hat{\varphi}_{2,4} & \hat{\varphi}_{2,5} & \hat{\varphi}_{2,6} & \hat{\varphi}_{2,7} & \hat{\varphi}_{2,8} \\ * & * & \hat{\varphi}_{3,3} & \hat{\varphi}_{3,4} & \hat{\varphi}_{3,5} & \hat{\varphi}_{3,6} & \hat{\varphi}_{3,7} & \hat{\varphi}_{3,8} \\ * & * & * & \bar{\varphi}_{4,4} & \bar{\varphi}_{4,5} & \bar{\varphi}_{4,6} & \hat{\varphi}_{4,7} & \bar{\varphi}_{4,8} \\ * & * & * & * & \bar{\varphi}_{5,5} & \bar{\varphi}_{5,6} & \hat{\varphi}_{5,7} & \bar{\varphi}_{5,8} \\ * & * & * & * & * & \bar{\varphi}_{6,6} & \hat{\varphi}_{6,7} & \bar{\varphi}_{6,8} \\ * & * & * & * & * & * & \hat{\varphi}_{7,7} & \hat{\varphi}_{7,8} \\ * & * & * & * & * & * & * & \bar{\varphi}_{8,8} \end{bmatrix} < 0 \quad (32)$$

Where:

$\hat{\varphi}_{1,1} = Q_{11} + R_{11} + Z_{11} + N_1 + N_1^T + M_1 + M_1^T - K_1A(t) - A^T(t)K_1^T,$
$\hat{\varphi}_{1,2} = Q_{12} + R_{12} + N_2^T + M_2^T - A^T(t)K_2^T + K_1B, \hat{\varphi}_{1,3} = N_3^T + M_3^T - A^T(t)K_3^T + K_1C(t),$
$\hat{\varphi}_{1,4} = N_4^T - N_1 + M_4^T - A^T(t)K_4^T, \hat{\varphi}_{1,5} = N_5^T + M_5^T - M_1 - A^T(t)K_5^T, \hat{\varphi}_{1,6} = N_6^T + M_6^T - A^T(t)K_6^T,$
$\hat{\varphi}_{1,7} = N_7^T + M_7^T - A^T(t)K_7^T + K_1D(t), \hat{\varphi}_{1,8} = P_{11} + P_{12} + Z_{12} + N_8^T + M_8^T - A^T(t)K_8^T - K_1,$
$\hat{\varphi}_{2,2} = Q_{22} + R_{22} + K_2B + B^T(t)K_2^T, \hat{\varphi}_{2,3} = B^TK_3^T + K_2C(t), \hat{\varphi}_{2,4} = -N_2 + B^T(t)K_4^T, \hat{\varphi}_{2,5} = -M_2 + B^T(t)K_5^T,$
$\hat{\varphi}_{2,6} = B^T(t)K_6^T, \hat{\varphi}_{2,7} = B^T(t)K_7^T + K_2D(t), \hat{\varphi}_{2,8} = B^T(t)K_8^T - K_2, \hat{\varphi}_{3,3} = -(1-\tau_d)Q_{22} + K_3C(t) + C^T(t)K_3^T,$
$\hat{\varphi}_{3,4} = -(1-\tau_d)Q_{12}^T - N_3 + C^T(t)K_4^T, \hat{\varphi}_{3,5} = -M_3 + C^T(t)K_5^T, \hat{\varphi}_{3,6} = C^T(t)K_6^T, \hat{\varphi}_{3,7} = C^T(t)K_7^T + K_3D,$
$\hat{\varphi}_{3,8} = C^T(t)K_8^T - K_3, \hat{\varphi}_{4,7} = -N_7^T + K_4D(t), \hat{\varphi}_{5,7} = P_{22} - (1-h_d)Z_{12} - M_7^T + K_5D(t), \bar{\varphi}_{6,7} = K_7D(t),$
$\hat{\varphi}_{7,7} = -(1-h_d)Z_{22} + K_7D(t) + D^T(t)K_7^T, \hat{\varphi}_{7,8} = D^T(t)K_8^T - K_7$

Define a Lyapunov functional candidate for system (28):

$$V(x(t)) = V_1(x(t)) + V_2(x(t)) + V_3(x(t)) + V_4(x(t)) + V_5(x(t)) \quad (33)$$

where, $V_1(x(t)), V_2(x(t)), V_3(x(t)), V_4(x(t))$ and $V_5(x(t))$ are defined in Eq. 11.

Similarly, the following equations hold:

$$2\zeta^T(t)\bar{N}\left[x(t) - x(t-\tau(t)) - \int_{t-\tau(t)}^{t} \dot{x}(s)\,ds\right] = 0 \quad (34)$$

$$2\zeta^T(t)\bar{M}\left[x(t) - x(t-h(t)) - \int_{t-h(t)}^{t} \dot{x}(s)\,ds\right] = 0 \quad (35)$$

$$2\zeta^T(t)\bar{K}\left[-Ax(t) + Bf(x(t)) + Cf(x(t-\tau(t))) + D\dot{x}(t-h(t)) - \dot{x}(t)\right] = 0 \quad (36)$$

where,

$\xi^T(t) = \left[x^T(t), f^T(x(t)), f^T(x-\tau(t)), x^T(t-\tau(t)), x^T(t-h(t)), f^T(x-h(t)), \dot{x}^T(t-h(t)), \dot{x}^T(t)\right],$
$A(t) = A + \Delta A(t), B(t) = B + \Delta B(t), C(t) = C + \Delta C(t), D(t) = D + \Delta D(t),$
$\bar{M}^T = [M_i]_{1\times 8}, \bar{N}^T = [N_i]_{1\times 8}, \bar{K}^T = [K_i]_{1\times 8}, i = 1, 2\ldots, 8$

Then, substituting Eq. 11-18, 22, 34-36 into Eq. 12, one obtains:

$$\dot{V}(x(t)) \le \zeta^T(t)\hat{\Pi}\zeta(t) \quad (37)$$

If $\hat{\Pi}$ is a negative definite matrix, this implies system Eq. 28 is asymptotically stable. The proof of the Theorem 2 is completed.

CONCLUSION

In present study, the robust stability of a class of neural networks with mixed time-varying delays and nonlinear perturbations has been studied. The mixed time delays comprise both the discrete and neutral-type time-varying delays. By constructing a new Lyapunov-Krasovskii functional and introducing some free-weighting matrices, sufficient delay-dependent stability conditions are derived in the form of a standard LMI. In addition, present results are shown to be generalizations of some previously published results. More importantly, the present results are also applicable to neural networks of neutral-type with multiple time delays.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation (No. 60974090) and by the Fundamental Research Funds for the Central Universities (No. CDJXS11172237).

REFERENCES

Cao, J. and J. Wang, 2003. Global asymptotic stability of a general class of recurrent neural networks with time-varying delays. Proc. IEEE Trans. Circuits Syst. I: Fundam. Theory Appl., 50: 34-44.

Cao, J.D. and J. Wang, 2005. Global exponential stability and periodicity of recurrent neural networks with time delays. IEEE Trans. Circuits Syst. Regul. Pap., 52: 920-931.

Kwon, O.M., J.H. Park and S.M. Lee, 2008. On robust stability criterion for dynamic systems with time-varying delays and nonlinear perturbations. Applied Math. Comput., 203: 937-942.

Lee, S.M., O.M. Kwon and J.H. Park, 2010. A novel delay-dependent criterion for delayed neural networks of neutral type. Phys. Lett. A., 374: 1843-1848.

Li, C., X. Liao and T. Huang, 2007. Global stability analysis for delayed neural networks via an interval matrix approach. IET Control Theory Appl., 1: 743-748.

Liao, X.F., G.R. Chen and E.N. Sanchez, 2002. Delay-dependent exponential stability analysis of delayed neural networks: An LMI approach. Neural Networks, 15: 855-866.

Lien, C.H., K.W. Yu, Y.F. Lin, Y.J. Chung and L.Y. Chung, 2008. Global exponential stability for uncertain delayed neural networks of neutral type with mixed time delays. IEEE Trans. Syst. Man Cybern. Part B Cybern., 38: 709-720.

Park, J.H., C.H. Park, O.M. Kwon and S.M. Lee, 2008. A new stability criterion for bidirectional associative memory neural networks of neutral-type. Applied Math. Comput., 199: 716-722.

Qiu, F., B.T. Cui and Y. Ji, 2010. A delay-dividing approach to stability of neutral system with mixed delays and nonlinear perturbations. Applied Math. Modell., 34: 3701-3707.

Qiu, J. and Q. Ren, 2006. Robust stability in interval delayed neural networks of neutral type. Intell. Comput., 4113: 451-456.

Wang, R., H. Lei and J. Wang, 2009. Stability analysis for a class of delay neural networks with nonlinear perturbations. Proceedings of the 4th International Conference on Computer Science and Education, July 25-28, Nanning, pp: 158-160.

Xie, L., T. Liu, G. Lu, J. Liu and S.T.C. Wong, 2006. Stochastic robust stability analysis for markovian jump discrete-time delayed neural networks with multiplicative nonlinear perturbations. Adv. Neural Networks, 3971: 172-178.

Xiong, W.L. and B.G. Xu, 2008. Some criteria for robust stability of cohen-grossberg neural networks with delays. Chaos, Solitons Fractals, 36: 1357-1365.

Yang, F.J., C.L. Zhang, C.Y. Chen and X.M. Chen, 2009. Global exponential stability of a class of neural networks with delays. Acta Math. Appl. Sin. E, 25: 43-50.

Zhang, H. and L.S. Chen, 2008. Asymptotic behavior of discrete solutions to delayed neural networks with impulses. Neurocomputing, 71: 1032-1038.

Zhang, H.G., Z.W. Liu and G.B. Huang, 2010. Novel delay-dependent robust stability analysis for switched neutral-type neural networks with time-varying delays via SC technique. IEEE Trans. Syst. Man Cybern. Part B Cybern., 40: 1480-1491.

Zhang, Q., X.P. Wei and J. Xu, 2007. A new global stability result for delayed neural networks. Nonlinear Anal. Real World Appl., 8: 1024-1028.

Zhu, J., Q.L. Zhang and C.Y. Yang, 2009. Delay-dependent robust stability for Hopfield neural networks of neutral-type. Neurocomputing, 72: 2609-2617.