Advances in Computational Design, *Vol. 9, No. 2 (2024) 97-113*
https://doi.org/10.12989/acd.2024.9.2.097

Stability of stochastic neutral neural networks with delays

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(Received January 8, 2024, Revised March 24, 2024, Accepted May 16, 2024)

Abstract. In this paper, we proposed a new class of stochastic neutral neural networks with uncertain and deterministic coefficients. Made the Sigmund activation and Lipschitz activation functions less conditional. The Lyapnov-Krasovskii functional is constructed. The linear matrix inequality (LMI) is constructed using Schur's lemma, and new criteria for the global asymptotic stability and global asymptotic robust stability of neural networks are obtained. Furthermore, we have verified that the method is effective and feasible through numerical examples.

Keywords: delay; deterministic and uncertain coefficients; neutral neural networks; robust stability; stochastic

1. Introduction

Neutral neural networks are widely involved in many fields, such as distributed networks, circuit networks, aerospace, and chemical engineering. It is an important class of nonlinear systems. In practical applications, the existence of time delay will have a great impact on the network. It will make the network unstable (Fazaeli *et al*. 2016, Habibi *et al*. 2017, 2019a, c, Safarpour *et al*. 2018, 2019b, 2020, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Ghazanfari *et al*. 2020, Chen *et al*. 2022b). Therefore, we should not only consider the impact of the past state on the present. In addition, the impact of time delay on the current state should also be considered. We know that many uncertain factors, such as data error, system error, parameter vibration and external disturbance, will affect the stability of neutral neural networks with time delay. Thus, in studying the stability of neutral neural networks with time delay, we also need to consider the effect of parameter uncertainty on the neural networks (Cao *et al*. 2022, Zhang *et al*. 2022, Wu *et al*. 2023, Huang *et al*. 2024, Liu *et al*. 2024). On the other hand, in many practical problems, such as biological systems, electronic circuits, chemical reaction processes, random interference is also a major factor affecting the dynamic behavior of neural networks. So, it is necessary to take the influence of random disturbances into account, when studying neutral neural networks with time delay. stochastic neutral neural networks has attracted the attention of many scholars and has produced many research results (Singh 2004, Liu *et al*. 2006, Gan and Xu 2010, Rakkiyappan and Balasubramaniam 2010, Wu *et al*. 2010, Zhang *et al*. 2010, 2019, Zhu and Cao 2010, Zhang and Wang 2012, Zheng *et al*. 2015, Song *et al*. 2016, Li *et al*. 2018, Imzegouan 2019, Cai *et al*. 2020,

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http://www.techno-press.org/?journal=acd&subpage=7 ISSN: 2383-8477 (Print), 2466-0523 (Online)

Dai and Hou 2021). Based on the above considerations, in this paper, we study the robust stability of neutral stochastic delay neural networks with parameter determinism and uncertainty.

2. Propaedeutics

It is necessary to study the robust stability of neutral stochastic systems with uncertain parameters because of the influence of uncertainty factors in the operation of neural networks (Dai *et al*. 2023a, b, Gu *et al*. 2023, Li *et al*. 2023, Peng *et al*. 2023, Sabzevari *et al*. 2023, Shariati *et al*. 2023, Xiang *et al*. 2023, Yang *et al*. 2023, Zhang *et al*. 2023a, b, Zhao *et al*. 2023, Zheng *et al*. 2023). Based on linear matrix inequality, Lyapunov-Krasovksii functional method is used to study the robust stability of the neutral random delay neural network with uncertain parameters, and the stability determination conditions are obtained, and it is easy to verify through the LMI control tool in Matlab toolbox, and presents numerical examples to illustrate the feasibility and effectiveness of the results (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020c, d, e, f, Bai *et al*. 2020, Cheshmeh *et al*. 2020, Li *et al*. 2020a, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020c, Xiong *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a, Tang *et al*. 2023). Consider the following neutral random time-delay neural network with uncertain parameters.

$$\begin{cases} d[x(t) - Dx(t-h(t))] \\ = \left[-(C+\Delta C)x(t) + (A+\Delta A)f\big(x(t)\big) + (B+\Delta B)f\Big(x\big(t-r(t)\big)\Big)\right]dt \\ +[(H_1+\Delta H_1)x(t) + (H_2+\Delta H_2)x(t-\tau(t))]d\omega(t), t>0. \\ x(t) = \phi(t), t\in[-\rho,0], \rho>0. \end{cases} \tag{1}$$

where $x(t) = (x_1(t), x_2(t), \cdots, x_n(t))^T \in R^n$, $C\ diag(c_1, c_2, \cdots, c_n), c_i > 0,\ i = 1,2,\cdots,n.\ f(u) = (f_1(u_1),\ f_2(u_2), \cdots, f_n(u_n))^T \in R^n$ denotes the activation function, A and B represent the Connection weight matrix and discrete delay connection weight matrix, respectively, $A,\ B,\ D \in R^{n\times n},\ H_i \in R^{n\times n}(i = 1,2),\ h(t), \tau(t), r(t)$ denotes different time delays, which are non-contributive and differentiable. In other words, $0 \le h(t) < h^*, 0 \le \rho = max\{h^*, \tau^*, r^*\}, \tau(t) < \tau^*, 0 \le r(t) < r^*,\ \dot{h}(t) \le \eta_1 < 1,\ \dot{\tau}(t) \le \eta_2 < 1,\ \dot{r}(t) \le \eta_3 < 1,\ \varphi \in C_{F_0}^b([-\rho, 0], R^n),\ \omega(t) = (\omega_1(t), \omega_2(t), \cdots, \omega_n(t))^T \in R^n$represents an n-wiener process defined on a complete probability space $(\Omega, \{F_t\}_{t\ge0}, P)$ with a natural filter $\{F_t\}_{t\ge0}\Delta C(t),\ \Delta A(t),\ \Delta B(t),\ \Delta H_1(t),\ \Delta H_2(t)$ is uncertain time-varying parameter satisfying

$$[\Delta C(t) \quad \Delta A(t) \quad \Delta B(t) \quad \Delta H_1(t) \quad \Delta H_2(t)] = MF(t)[N_1 \quad N_2 \quad N_3 \quad N_4 \quad N_5] \tag{2}$$

where $M, N_i(i = 1, \cdots, n)$ are known appropriate dimensional constant matrices, $F(t)$ is an unknown time-varying matrix function satisfying

$$F^T(t)F(t) \le \mathrm{I}. \tag{3}$$

Assume that $f_i(\bullet), (i = 1, \cdots, n)$, the activation function of each neuron in system (1), is bounded and satisfies the following conditions

$$l_i \le \frac{f_i(u) - f_i(v)}{u - v} \le l_i^+, \tag{1}$$

where, l_i, l_i^* $(i = 1, \cdots, n)$ represent constants, and positive, negative and zero can be taken, thus reducing the conditional restriction of Sigmond activation function and Lipschitz type activation function (Lu *et al*. 2023a, b, Ma *et al*. 2023, Tang *et al*. 2023, Wang *et al*. 2023b).

2.1 Hypothesis

Assuming that all eigenvalues of matrix $D$are inside the unit circle (Habibi *et al*. 2016, 2018a, b, 2019b, d, e, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a, Zhu *et al*. 2022). It is important to note that hypothesis 1 guarantees the stability of the differential system $x(t) - Dx(t - h(t)) = 0$. Firstly, the global asymptotic mean square stability of a neutral random delay neural network with fixed parameters is considered

$$\begin{cases} d[x(t) - Dx(t - h(t))] = [-Cx(t) + Af(x(t)) + Bf(x(t - r(t)))]dt \\ +[H_1 x(t) + H_2 x(t - \tau(t))]d\omega(t), t > 0. \\ x(t) = \phi(t), t \in [-\rho, 0], \rho > 0. \end{cases} \tag{5}$$

2.1.1 Lemma 1 (Singh 2004)

There are matrices U, V, W, M,with the right dimensions, and $M = M^T$. if and only if there is any scalar $\varepsilon > 0$, such that

$$M + \varepsilon^{-1} U U^T + \varepsilon W^T W < 0 \tag{6}$$

then for all $VV^T \leq I$,the following holds

$$M + UVW + W^T U^T V^T < 0 \tag{7}$$

2.1.2 Lemma 2 (Liu et al. 2006)

For an any constant symmetric matrix $M, M = M^T > 0$, a scalar $\gamma > 0$, and a vector function $\omega: [0, \gamma] \to R^n$ that makes the following integral exist (Tian *et al*. 2022, Lin *et al*. 2023, Yao *et al*. 2024), then the following inequality holds

$$\left[\int_0^\gamma \omega(s) ds\right]^T M \left[\int_0^\gamma \omega(s) ds\right] \leq \gamma \int_0^\gamma \omega^T(s) M \omega(s) ds \tag{8}$$

2.1.3 Definition 1

If the solution $x(t, t_0, \phi)$ of system (5) satisfies

$$\lim_{t \to +\infty} E\|x(t, t_0, \phi)\|^2 = 0, t \geq t_0. \tag{9}$$

then the trivial solution of system (5) is globally asymptotically stable in the mean square sense (Chen *et al*. 2022a, Tang *et al*. 2024, Yang *et al*. 2024).

2.1.4 Definition 2

If the solution $x(t, t_0, \phi)$ of system (1) satisfies

$$\lim_{t \to +\infty} E\|x(t, t_0, \phi)\|^2 = 0, t \geq t_0. \tag{10}$$

then the trivial solution of system (1) is globally robust and stochastic asymptotically stable in the mean square sense.

3. Stability analysis

Define the symbol $L_1 = diag\{l_1 l_1^+, \cdots, l_n l_n^+\}, L_2 = diag\{l_1 + l_1^+, \cdots, l_n + l_n^+\}$.

3.1 Theorem 1

If there exist any matrices $P > 0, Q_i > 0, R_j > 0, (i = 1,2,3, j = 1,2)$, $U_1 = diag\ \{u_{11}, \cdots, u_{1n}\} \geq 0$, $U_2 = diag\{u_{21}, \cdots, u_{2n}\} \geq 0$,such that

$$S=\begin{bmatrix} W_{11} & CPD & 0 & 0 & PA+L_2U_1 & PB & H_1^{T}P \\ * & -(1-\hbar_1)Q_1 & 0 & 0 & -D^{T}PA & -D^{T}PB & H_2^{T}P \\ * & * & -2L_1U_1 & 0 & 0 & L_2U_2 & 0 \\ * & * & * & -(1-\hbar_2)Q_2 & 0 & 0 & 0 \\ * & * & * & * & Q_3-2U_1 & 0 & 0 \\ * & * & * & * & * & -2U_2-(1-\hbar_2)Q_3 & 0 \\ * & * & * & * & * & * & -P \end{bmatrix} \quad (11)$$

<0,

where, $\Omega_{11} = -PC - CP + Q_1 + Q_2 + h^{*2}R_1 + \tau^{*2}R_2 - 2L_1U_1$, * represents the element obtained from symmetry.

3.1.1 Proof

Define a functional for System (5)

$$\begin{aligned} V(t) &= [x(t) - Dx(t-h(t))]^T P[x(t) - Dx(t-h(t))] + \int_{t-h(t)}^{t} x^T(s)Q_1x(s)\,ds \\ &+h^*\int_{-h^*}^{0}\int_{t+\beta}^{t} x^T(s)R_1x(s)\,ds\,d\beta + \int_{t-r(t)}^{t} x^T(s)Q_2x(s)\,ds \\ &+\tau^*\int_{-\tau^*}^{0}\int_{t+\beta}^{t} x^T(s)R_2x(s)\,ds\,d\beta + \int_{t-\tau(t)}^{t} f^T(x(s))Q_3f(x(s))\,ds. \end{aligned} \quad (12)$$

where,$P, Q_i, R_j (i = 1,2,3, j = 1,2)$ are Positive definite matrices. According to the $It\hat{o}$differential mean value theorem, take the random derivative with respect to $V(t)$ along the orbital of system (5).

$$dV(t) = \begin{Bmatrix} [x(t) - Dx(t-h(t))]^T \times \\ P[H_1x(t) + H_2x(t-\tau(t))] \end{Bmatrix} d\omega(t) + \quad (13)$$

$$\left\{\begin{array}{c}\begin{bmatrix}x(t)-\\Dx(t-h(t))\end{bmatrix}^T P\begin{bmatrix}-Cx(t)\\+Af(x(t))\\+Bf\left(x(t-r(t))\right)\end{bmatrix}+\begin{bmatrix}H_1x(t)+\\H_2x(t-\tau(t))]^T\end{bmatrix}P\begin{bmatrix}H_1x(t)\\+H_2x(t-\tau(t))\end{bmatrix}\\ +x^T(t)Q_1x(t)+h^{*2}x^T(t)R_1x(t)-\left(1-\dot{h}(t)\right)x^T(t-h(t))Q_1x(t-h(t))\\ -h^*\int_{t-h^*}^{t}x^T(s)R_1x(s)\,ds+x^T(t)Q_2x(t)+\tau^{*2}x^T(t)R_2x(t)\\ -(1-\dot{\tau}(t))x^T(t-h(t))Q_2x(t-h(t))-\tau^*\int_{t-\tau^*}^{t}x^T(s)R_2x(s)\,ds\\ +f^T(x(t))Q_3f(x(t))-(1-\dot{r}(t))f^T\left(x(t-r(t))\right)\times Q_3f(x(t-r(t)))\end{array}\right\}dt$$

$$+h^*\int_{-h^*}^{0}\int_{t+\beta}^{t}x^T(s)R_1x(s)\,ds\,d\beta+\int_{t-r(t)}^{t}x^T(s)Q_2x(s)\,ds$$

$$+\tau^*\int_{-\tau^*}^{0}\int_{t+\beta}^{t}x^T(s)R_2x(s)\,ds\,d\beta+\int_{t-\tau(t)}^{t}f^T(x(s))Q_3f(x(s))\,ds.$$

By applying Lemma 2, we can get

$$\begin{aligned}&h^*\int_{t-h^*}^{t}x^T(s)R_1x(s)ds\le -h^*\int_{t-h(t)}^{t}x^T(s)R_1x(s)ds\\&\le -\frac{h^*}{h(t)}(\int_{t-h(t)}^{t}x(s)ds)^TR_1(\int_{t-h(t)}^{t}x(s)ds)\\&\le -(\int_{t-h(t)}^{t}x(s)ds)^TR_1(\int_{t-h(t)}^{t}x(s)ds),\qquad \tau^*\int_{t-\tau^*}^{t}x^T(s)R_2x(s)ds\\&\le -\tau^*\int_{t-\tau(t)}^{t}x^T(s)R_2x(s)ds\le -\frac{\tau^*}{\tau(t)}(\int_{t-\tau(t)}^{t}x(s)ds)^TR_2(\int_{t-\tau(t)}^{t}x(s)ds)\\&\le -(\int_{t-\tau(t)}^{t}x(s)ds)^TR_2(\int_{t-\tau(t)}^{t}x(s)ds).\end{aligned}\tag{14}$$

By (4), it holds that

$$\begin{aligned}&[f_i(x_i(t))-l_ix_i(t)][f_i(x_i(t))-l_i^+x_i(t)]\le 0, f_i(0)=0, i=1,\cdots,n,\\&[f_i(x_i(t-r(t)))-l_ix_i(t-r(t))]\times[f_i(x_i(t-r(t)))-l_i^+x_i(t-r(t))]\\&\le 0, f_i(0)=0, i=1,\cdots,n.\end{aligned}\tag{15}$$

Then from$U_1=diag\{u_{11},\cdots,u_{1n}\}\ge 0, U_2=diag\{u_{21},\cdots,u_{2n}\}\ge 0$,we can get

$$\begin{aligned}&dV(t)\le dV(t)\ -2\textstyle\sum_{i=1}^{n}u_{1i}\,[f_i(x_i(t))-l_ix_i(t)][f_i(x_i(t))-l_i^+x_i(t)]\\&-2\sum_{i=1}^{n}u_{2i}\left[f_i\left(x_i(t-r(t))\right)-l_ix_i(t-r(t))\right]\times\ [f_i(x_i(t-r(t)))-l_i^+x_i(t-r(t))]\\&\le\{\xi^T(t)\Sigma_1\xi(t)\}dt\ +\{2x^T(t)P[H_1x(t)+H_2x(t-\tau(t))]\}d\omega(t).\end{aligned}\tag{16}$$

where

$$\Sigma_1 = \begin{bmatrix} \Omega_{11} & CPD & 0 & 0 & PA+L_2U_1 & PB \\ * & -(1-\eta_1)Q_1 & 0 & 0 & -D^T PA & -D^T PB \\ * & * & -2L_1U_1 & 0 & 0 & L_2U_2 \\ * & * & * & -(1-\eta_2)Q_2 & 0 & 0 \\ * & * & * & * & Q_3-2U_1 & 0 \\ * & * & * & * & * & -2U_2-(1-\eta_2)Q_3 \end{bmatrix} + \begin{bmatrix} H_1^{\mathrm{T}}P \\ H_2^{\mathrm{T}}P \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} P^{-1} \begin{bmatrix} H_1^{\mathrm{T}}P \\ H_2^{\mathrm{T}}P \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}^{\mathrm{T}}, \tag{17}$$

$$\xi(t)=\left[x^{\mathrm{T}}(t) \quad x^{\mathrm{T}}(t-h(t)) \quad x^{\mathrm{T}}(t-r(t)) \quad x^{\mathrm{T}}(t-\tau(t)) \quad f^{\mathrm{T}}(x(t)) \quad f^{\mathrm{T}}(x(t-r(t)))\right]^{\mathrm{T}}. \tag{18}$$

From $\Sigma < 0$ in (6) and lemma 2 (Schur complement lemma), we can get $\Sigma_1 < 0$. Obviously, there must exist a scalar $\gamma > 0$ that makes

$$\Sigma_1 + diag\{\gamma I \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\} < 0. \tag{19}$$

Take the mathematical expectation of both sides of (8), and we get

$$\frac{dEV(t)}{dt} \le E[\xi^T(t)\Sigma_1\xi(t)] \le -\gamma E\|x(t)\|^2. \tag{20}$$

According to definition 1, system (5) is globally asymptotically stable (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Liu *et al.* 2020a, b, 2021b, Wang *et al.* 2020, Zare *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, b, Guo *et al.* 2021a, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021, Shao *et al.* 2021, Wu and Habibi 2021, Zhang *et al.* 2021, Kong *et al.* 2022).

3.2 Theorem 2

If there exist any matrices $P > 0, Q_i > 0, R_j > 0, (i = 1,2,3, j = 1,2)$, $\varepsilon_1 > 0, \varepsilon_2 > 0$, $U_1 = diag\{u_{11}, \cdots, u_{1n}\} \ge 0, U_2 = diag\{u_{21}, \cdots, u_{2n}\} \ge 0$, such that

$$\Lambda = \begin{bmatrix} \Psi_{11} & CPD & 0 & \varepsilon_2 N_4^{\mathrm{T}} N_5 & \Psi_{15} & \Psi_{16} & H_1^{\mathrm{T}}P & PM & 0 \\ * & \Psi_{22} & 0 & 0 & -D^T PA & -D^T PB & H_2^{\mathrm{T}}P & -D^T PM & 0 \\ * & * & -2L_1U_1 & 0 & 0 & L_2U_2 & 0 & 0 & 0 \\ * & * & * & \Psi_{44} & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & \Psi_{55} & \varepsilon_1 N_2^{\mathrm{T}} N_3 & 0 & 0 & 0 \\ * & * & * & * & * & \Psi_{66} & 0 & 0 & 0 \\ * & * & * & * & * & * & -P & 0 & PM \\ * & * & * & * & * & * & * & -\varepsilon_1 \mathrm{I} & 0 \\ * & * & * & * & * & * & * & * & -\varepsilon_2 \mathrm{I} \end{bmatrix} < 0 \tag{21}$$

then system (1) is Globally asymptotically robust stability in the mean square sense (Ghosh *et al.* 2022, Liu *et al.* 2023, Dang *et al.* 2024). Where,

$$\begin{aligned}&\Psi_{11}=-PC-CP+Q_1+Q_2+h^{*2}R_1+\tau^{*2}R_2-2L_1U_1+\varepsilon_1N_1^TN_1+\varepsilon_2N_4^TN_4,\\&\Psi_{15}=PA+L_2U_1-\varepsilon_1N_1^TN_2,\Psi_{16}=PB-\varepsilon_1N_1^TN_3,\Psi_{22}=-(1-\eta_1)Q_1,\\&\Psi_{44}=-(1-\eta_2)Q_2+\varepsilon_1N_5^TN_5,\Psi_{66}=Q_3-2U_1+\varepsilon_1N_2^TN_2,\end{aligned}\tag{22}$$

$*$ denotes the element obtained by symmetry.

3.3 Proof:

According to Equations (2) and (3), replace C,A,B,H_1,H_2 with $C+\Delta C,A+\Delta A,B+\Delta B,H_1+\Delta H_1,\ H_2+\Delta H_2,$ and get

$$\Lambda_1=\Sigma+\begin{bmatrix}PA\\-D^TPM\\0\\0\\0\\0\\0\end{bmatrix}F(t)\begin{bmatrix}-N_1^T\\0\\0\\0\\N_2^T\\N_3^T\\0\end{bmatrix}^T+\begin{bmatrix}-N_1^T\\0\\0\\0\\N_2^T\\N_3^T\\0\end{bmatrix}F^T(t)\begin{bmatrix}PA\\-D^TPM\\0\\0\\0\\0\\0\end{bmatrix}^T+\begin{bmatrix}0\\0\\0\\0\\0\\0\\PM\end{bmatrix}F(t)\begin{bmatrix}N_4^T\\0\\0\\N_5^T\\0\\0\\0\end{bmatrix}^T+\begin{bmatrix}0\\0\\0\\0\\0\\0\\PM\end{bmatrix}^T F(t)\begin{bmatrix}N_4^T\\0\\0\\N_5^T\\0\\0\\0\end{bmatrix}\tag{23}$$

According to lemma 1, $\Lambda_1<0$, and $\Lambda_1$can be equivalent to

$$\Lambda_2=\Sigma+\varepsilon_1^{-1}\begin{bmatrix}PA\\-D^TPM\\0\\0\\0\\0\\0\end{bmatrix}\begin{bmatrix}PA\\-D^TPM\\0\\0\\0\\0\\0\end{bmatrix}^T+\varepsilon_1\begin{bmatrix}-N_1^T\\0\\0\\0\\N_2^T\\N_3^T\\0\end{bmatrix}\begin{bmatrix}-N_1^T\\0\\0\\0\\N_2^T\\N_3^T\\0\end{bmatrix}^T+\varepsilon_2^{-1}\begin{bmatrix}0\\0\\0\\0\\0\\0\\PM\end{bmatrix}\begin{bmatrix}0\\0\\0\\0\\0\\0\\PM\end{bmatrix}^T+\varepsilon_2\begin{bmatrix}N_4^T\\0\\0\\N_5^T\\0\\0\\0\end{bmatrix}\begin{bmatrix}N_4^T\\0\\0\\N_5^T\\0\\0\\0\end{bmatrix}^T\tag{24}$$

From $\Lambda<0$ in (9) and lemma 2 (Schur complement lemma), we can get $\Lambda_2<0$. By the theorem 1, the uncertain neutral neural network (1) is the global asymptotic robust stability. That's the end of the proof. We have the following results on the basis of theorem 1 (Yu *et al.* 2021, Xu and Guo 2022, Guo and Hu 2023, Ban *et al.* 2024).

3.3.1 Remark 1

When$D=0$, system (5) is converted to the following system:

$$\begin{aligned}&dx(t)=\begin{bmatrix}-(C+\Delta C)x(t)+(A+\Delta A)f(x(t))\\+(B+\Delta B)f(x(t-r(t)))\end{bmatrix}dt\\&+[(H_1+\Delta H_1)x(t)+(H_2+\Delta H_2)x(t-\tau(t))]d\omega(t),t>0.\\&x(t)=\varphi(t),t\in[-\rho,0],\rho>0.\end{aligned}\tag{25}$$

3.3.2 Corollary 1

The equilibrium point of system (10) is globally asymptotically mean square stable, if there is

$$\begin{aligned}&P>0,Q_i>0,R_j>0,(i=1,2,3,j=1,2),U_1\\&=diag\{u_{11},\cdots,u_{1n}\}\geq 0,U_2=diag\{u_{21},\cdots,u_{2n}\}\geq 0\end{aligned}\tag{26}$$

such that

$$\begin{bmatrix} \Psi_{11} & 0 & 0 & PA+L_2U_1 & PB & H_1^{\mathrm{T}}P \\ * & -2L_1U_1 & 0 & 0 & L_2U_2 & H_2^{\mathrm{T}}P \\ * & * & -(1-\eta_2)Q_2 & 0 & 0 & 0 \\ * & * & * & Q_3-2U_1 & 0 & 0 \\ * & * & * & * & -2U_2-(1-\eta_2)Q_3 & 0 \\ * & * & * & * & * & -P \end{bmatrix} < 0, \quad (27)$$

where

$$\Psi_{11} = -PC - CP + Q_1 + Q_2 + h^{*2}R_1 + \tau^{*2}R_2 - 2L_1U_1 \quad (28)$$

$*$denotes the element obtained by symmetry.

3.3.3 Remark 2

If no random disturbance, the system (5) can be simplified to the following system

$$\begin{cases} \dot{x}(t) - \dot{D}x(t-h(t)) = -Cx(t) + Af(x(t)) + Bf(x(t-r(t))), & t > 0 \\ x(t) = \varphi(t), \quad t \in [-\rho, 0], & \rho > 0. \end{cases} \quad (29)$$

3.3.4 Corollary 2

The equilibrium point of system (12) is global asymptotic stability, if there is

$$\begin{aligned} &P > 0, Q_i > 0, R_i > 0, (i = 1,2,3, j = 1,2), \\ &U_i = diag\{u_{11}, \cdots, u_{1n}\} \geq 0, U_2 = diag\left\{u_{21}, \cdots, u_{2n}\right\} \geq 0 \end{aligned} \quad (30)$$

such that

$$\begin{bmatrix} \Psi_{11} & CPD & 0 & 0 & PA+L_2U_1 & PB \\ * & -(1-\eta_1)Q_1 & 0 & 0 & -D^TPA & -D^TPB \\ * & * & -2L_1U_1 & 0 & 0 & L_2U_2 \\ * & * & * & -(1-\eta_2)Q_2 & 0 & 0 \\ * & * & * & * & Q_3-2U_1 & 0 \\ * & * & * & * & * & -2U_2-(1-\eta_2)Q_3 \end{bmatrix} < 0, \quad (31)$$

where $\Psi_{11} = -PC - CP + Q_1 + Q_2 + h^{*2}R_1 + \tau^{*2}R_2 - 2L_1U_1$, $*$ denotes the element obtained by symmetry.

4. Numerical examples

In this section, A numerical example is given to illustrate the effectiveness of the theorem 2 related to the neural network system (1). It can be proved to be globally asymptotically robust and stable (Ebrahimi *et al*. 2019b, c, Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Ebrahimi *et al*. 2020b, Habibi *et al*. 2020, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, b, Shokrgozar *et al*. 2020). The coefficients in the neutral neural network with random delay are considered as follows:

$$A = \begin{bmatrix} -0.5 & 0.2 \\ 0.4 & -0.1 \end{bmatrix} \tag{32a}$$

$$B = \begin{bmatrix} 0.1 & -1 \\ -1.4 & 0.4 \end{bmatrix} \tag{32b}$$

$$C = \begin{bmatrix} 1.15 & 0 \\ 0 & 1.2 \end{bmatrix} \tag{32c}$$

$$D = \begin{bmatrix} 0.35 & 0.2 \\ 0 & 0.6 \end{bmatrix}, \tag{32d}$$

$$H_1 = \begin{bmatrix} 0.23 & 0.1 \\ 0.3 & 0.2 \end{bmatrix} \tag{32e}$$

$$H_2 = \begin{bmatrix} 0.1 & -0.2 \\ 0.2 & 0.3 \end{bmatrix} \tag{32f}$$

$$M = \begin{bmatrix} 0.1 \\ 0.2 \end{bmatrix} \tag{32g}$$

$$N_1 = [0.1 \quad 0.2] \tag{32h}$$

$$N_2 = [0.5 \quad 0.1] \tag{32i}$$

$$N_3 = [-0.2 \quad 0.2] \tag{32j}$$

$$N_4 = [-0.1 \quad 0.2] \tag{32l}$$

$$N_5 = [0.3 \quad 0.1] \tag{32m}$$

$$l_1 = 0, l_1^+ = 1, l_2 = 0, l_2^+ = 1, \tag{32n}$$

Therefore $L_1 = 0, L_2 = diag\{1,1\}$, Let $\eta_1 = \eta_2 = \eta_2 = 0.0035$, $\rho = h^* = r^* = \tau^* = 1$. By using the toolbox in MATLAB LMI, the elements in feasible solution (9) can be obtained as follows:

$$P = \begin{bmatrix} 408.1627 & 22.2318 \\ 22.2318 & 263.0276 \end{bmatrix} \tag{33).a}$$

$$Q_1 = Q_2 = \begin{bmatrix} 294.6094 & 84.9579 \\ 84.9579 & 287.3664 \end{bmatrix}, \tag{33).b}$$

$$Q_3 = \begin{bmatrix} 184.9382 & -61.1947 \\ -61.1947 & 125.9148 \end{bmatrix} \tag{33).c}$$

$$R_1 = R_2 = \begin{bmatrix} 0.0037 & 0.0001 \\ 0.0001 & 0.0030 \end{bmatrix}, \tag{33).d}$$

$$U_1 = \begin{bmatrix} 195.9182 & 0 \\ 0 & 123.3233 \end{bmatrix} \quad (33).e$$

$$U_2 = \begin{bmatrix} 250.3028 & 0 \\ 0 & 161.7723 \end{bmatrix}, \quad (33).f$$

According to theorem (2), the system is globally asymptotically robust and stable in the mean square sense (Wang *et al*. 2023a, 2024a, b).

5. Conclusions

This paper mainly studies the stochastic delay neutral neural networks with certain and uncertain coefficients. The restriction of activation function is weakened. The Lyapnov-Krasovskii function is constructed, and the global asymptotic stability and global asymptotic robust stability of the system are proved by LMI. The research results improve the ability of neural network to resist white noise interference to a certain extent, and provide a strong theoretical basis for computer simulation.

References

Adamian, A., Safari, K.H., Sheikholeslami, M., Habibi, M., Al-Furjan, M. and Chen, G. (2020), "Critical temperature and frequency characteristics of GPLs-reinforced composite doubly curved panel", *Appl. Sci.*, **10**(9), 3251. https://doi.org/10.3390/app10093251.

Al-Furjan, M., Dehini, R., Khorami, M., Habibi, M. and won Jung, D. (2020a), "On the dynamics of the ultra-fast rotating cantilever orthotropic piezoelectric nanodisk based on nonlocal strain gradient theory", *Compos. Struct.*, 112990. https://doi.org/10.1016/j.compstruct.2020.112990.

Al-Furjan, M., Fereidouni, M., Habibi, M., Abd Ali, R., Ni, J. and Safarpour, M. (2020b), "Influence of in-plane loading on the vibrations of the fully symmetric mechanical systems via dynamic simulation and generalized differential quadrature framework", *Eng. Comput.*, 1-23. https://doi.org/10.1007/s00366-020-01177-7.

Al-Furjan, M., Fereidouni, M., Sedghiyan, D., Habibi, M. and won Jung, D. (2020c), "Three-dimensional frequency response of the CNT-Carbon-Fiber reinforced laminated circular/annular plates under initially stresses", *Compos. Struct.*, 113146. https://doi.org/10.1016/j.compstruct.2020.113146.

Al-Furjan, M., Habibi, M., won Jung, D. and Safarpour, H. (2020d), "Vibrational characteristics of a higher-order laminated composite viscoelastic annular microplate via modified couple stress theory", *Compos. Struct.*, 113152. https://doi.org/10.1016/j.compstruct.2020.113152.

Al-Furjan, M., Moghadam, S.A., Dehini, R., Shan, L., Habibi, M. and Safarpour, H. (2020e), "Vibration control of a smart shell reinforced by graphene nanoplatelets under external load: Semi-numerical and finite element modeling", *Thin Wall. Struct.*, 107242. https://doi.org/10.1016/j.tws.2020.107242.

Al-Furjan, M., Oyarhossein, M.A., Habibi, M., Safarpour, H. and Jung, D.W. (2020f), "Frequency and critical angular velocity characteristics of rotary laminated cantilever microdisk via two-dimensional analysis", *Thin Wall. Struct.*, **157**, 107111. https://doi.org/10.1016/j.tws.2020.107111.

Alipour, M., Torabi, M.A., Sareban, M., Lashini, H., Sadeghi, E., Fazaeli, A., Habibi, M. and Hashemi, R. (2020), "Finite element and experimental method for analyzing the effects of martensite morphologies on the formability of DP steels", *Mech. Based Des. Struct.*, **48**(5), 525-541. https://doi.org/10.1080/15397734.2019.1633343.

Bai, Y., Alzahrani, B., Baharom, S. and Habibi, M. (2020), "Semi-numerical simulation for vibrational responses of the viscoelastic imperfect annular system with honeycomb core under residual pressure", *Eng*. *Comput*., 1-26. https://doi.org/10.1007/s00366-020-01191-9.

Ban, Y., Liu, Y., Yin, Z., Liu, X., Liu, M., Yin, L., Li, X. and Zheng, W. (2024), "Micro-directional propagation method based on user clustering", *Comput*. *Inform*., **42**(6), 1445-1470. https://doi.org/10.31577/cai_2023_6_1445.

Cai, T., Cheng, P. and Wu, Z. (2020). "Robust exponential stability of uncertain discrete-time stochastic neural networks with impulses", *2020 Chinese Control And Decision Conference (CCDC)*, 22-24, August, 2020. https://doi.org/10.1109/CCDC49329.2020.9164336.

Cao, C., Wang, J., Kwok, D., Cui, F., Zhang, Z., Zhao, D., Li, M.J. and Zou, Q. (2022), "webTWAS: a resource for disease candidate susceptibility genes identified by transcriptome-wide association study", *Nucl*. *Acids Res*., **50**(D1), D1123-D1130. https://doi.org/10.1093/nar/gkab957.

Chen, B., Hu, J., Zhao, Y. and Ghosh, B.K. (2022a), "Finite-time observer based tracking control of uncertain heterogeneous underwater vehicles using adaptive sliding mode approach", *Neurocomputing*. **481**, 322-332. https://doi.org/10.1016/j.neucom.2022.01.038.

Chen, F., Chen, J., Duan, R., Habibi, M. and Khadimallah, M.A. (2022b), "Investigation on dynamic stability and aeroelastic characteristics of composite curved pipes with any yawed angle", *Compos*. *Struct*., 115195. https://doi.org/10.1016/j.compstruct.2022.115195.

Cheshmeh, E., Karbon, M., Eyvazian, A., Jung, D.w., Habibi, M. and Safarpour, M. (2020), "Buckling and vibration analysis of FG-CNTRC plate subjected to thermo-mechanical load based on higher order shear deformation theory", *Mech*. *Based Des*. *Struct*., 1-24. https://doi.org/10.1080/15397734.2020.1744005.

Dai, L. and Hou, Y. (2021), "Mean-square exponential input-to-state stability of stochastic quaternion-valued neural networks with time-varying delays", *Adv*. *Differ*. *Eq*., **2021**(1), 362. https://doi.org/10.1186/s13662-021-03509-3.

Dai, Z., Jiang, Z., Zhang, L. and Habibi, M. (2021a), "Frequency characteristics and sensitivity analysis of a size-dependent laminated nanoshell", *Adv*. *Nano Res*., **10**(2), 175. https://doi.org/10.12989/anr.2021.10.2.175.

Dai, Z., Tang, H., Wu, S., Habibi, M., Moradi, Z. and Ali, H.E. (2023a), "Nonlinear consecutive dynamic instabilities of thermally shocked composite circular plates on the softening elastic foundation", *Thin Wall*. *Struct*., **186**, 110645. https://doi.org/10.1016/j.tws.2023.110645.

Dai, Z., Wu, S., Habibi, M. and Ali, H.E. (2023b), "Application of point interpolation mesh-free method for magneto/electro rheological vibrations of sandwich conical panels", *Aerosp*. *Sci*. *Technol*., 108180. https://doi.org/10.1016/j.ast.2023.108180.

Dai, Z., Zhang, L., Bolandi, S.Y. and Habibi, M. (2021b), "On the vibrations of the non-polynomial viscoelastic composite open-type shell under residual stresses", *Compos*. *Struct*., 113599. https://doi.org/10.1016/j.compstruct.2021.113599.

Dang, W., Cai, L., Liu, M., Li, X., Yin, Z., Liu, X., Yin, L. and Zheng, W. (2024), "Increasing text filtering accuracy with improved LSTM", *Comput*. *Inform*., **42**(6), 1491-1517. https://doi.org/10.31577/cai_2023_6_1491.

Ebrahimi, F., Habibi, M. and Safarpour, H. (2019a), "On modeling of wave propagation in a thermally affected GNP-reinforced imperfect nanocomposite shell", *Eng*. *Comput*., **35**(4), 1375-1389. https://doi.org/10.1007/s00366-018-0669-4.

Ebrahimi, F., Hajilak, Z.E., Habibi, M. and Safarpour, H. (2019b), "Buckling and vibration characteristics of a carbon nanotube-reinforced spinning cantilever cylindrical 3D shell conveying viscous fluid flow and carrying spring-mass systems under various temperature distributions", *Proceedings of the Institution of Mechanical Engineers*, *Part C: Journal of Mechanical Engineering Science*, **233**(13), 4590-4605. https://doi.org/10.1177/0954406219832323.

Ebrahimi, F., Hashemabadi, D., Habibi, M. and Safarpour, H. (2020a), "Thermal buckling and forced vibration characteristics of a porous GNP reinforced nanocomposite cylindrical shell", *Microsyst*. *Technol*., **26**(2), 461-473. https://doi.org/10.1007/s00542-019-04542-9.

Ebrahimi, F., Mohammadi, K., Barouti, M.M. and Habibi, M. (2019c), "Wave propagation analysis of a spinning porous graphene nanoplatelet-reinforced nanoshell", *Waves Random Complex Med*., 1-27.

https://doi.org/10.1080/17455030.2019.1694729.

Ebrahimi, F., Supeni, E.E.B., Habibi, M. and Safarpour, H. (2020b), "Frequency characteristics of a GPL-reinforced composite microdisk coupled with a piezoelectric layer", *Eur. Phys. J. Plus*, **135**(2), 144. https://doi.org/10.1140/epjp/s13360-020-00217-x.

Esmailpoor Hajilak, Z., Pourghader, J., Hashemabadi, D., Sharifi Bagh, F., Habibi, M. and Safarpour, H. (2019), "Multilayer GPLRC composite cylindrical nanoshell using modified strain gradient theory", *Mech. Based Des. Struct.*, **47**(5), 521-545. doi/10.1080/15397734.2019.1566743.

Fazaeli, A., Habibi, M. and Ekrami, A.a. (2016), "Experimental and finite element comparison of mechanical properties and formability of dual phase steel and ferrite - pearlite steel with the same chemical composition", *Metall. Eng.*, **19**(2), 84-93. http://doi.org/10.22076/me.2017.41458.1064.

Gan, Q. and Xu, R. (2010), "Global robust exponential stability of uncertain neutral high-order stochastic hopfield neural networks with time-varying delays", *Neural Proc. Lett.*, **32**(1), 83-96. https://doi.org/10.1007/s11063-010-9146-9.

Ghazanfari, A., Soleimani, S.S., Keshavarzzadeh, M., Habibi, M., Assempuor, A. and Hashemi, R. (2020), "Prediction of FLD for sheet metal by considering through-thickness shear stresses", *Mech. Based Des. Struct.*, **48**(6), 755-772. https://doi.org/10.1080/15397734.2019.1662310.

Ghosh, B., Chen, B., Hu, J. and Zhao, Y. (2022), "Finite-time velocity-free rendezvous control of multiple AUV systems with intermittent comunication", *IEEE T. Syst. Man Cy Syst.*, **52**(10), 6618-6629. https://doi.org/10.1109/TSMC.2022.3148295.

Gu, X., He, J., Wang, Z., Li, M., Habibi, M. and Hashemabadi, D. (2023), "Application of hyperbolic differential quadrature method for vibration responses of the electrorheological disk", *Eng. Anal. Bound. Elem.*, **155** 599-615. https://doi.org/10.1016/j.enganabound.2023.05.035.

Guo, C. and Hu, J. (2023), "Time base generator-based practical predefined-time stabilization of high-order systems with unknown disturbance", *IEEE T. Circuits II*, **70**(7), 2670-2674. https://doi.org/10.1109/TCSII.2023.3242856.

Guo, J., Baharvand, A., Tazeddinova, D., Habibi, M., Safarpour, H., Roco-Videla, A. and Selmi, A. (2021a), "An intelligent computer method for vibration responses of the spinning multi-layer symmetric nanosystem using multi-physics modeling", *Eng. Comput.*, 1-22. https://doi.org/10.1007/s00366-021-01433-4.

Guo, Y., Mi, H. and Habibi, M. (2021b), "Electromechanical energy absorption, resonance frequency, and low-velocity impact analysis of the piezoelectric doubly curved system", *Mech. Syst. Signal Pr.*, **157**, 107723. https://doi.org/10.1016/j.ymssp.2021.107723.

Habibi, M., Darabi, R., Sa, J.C.d. and Reis, A. (2021), "An innovation in finite element simulation via crystal plasticity assessment of grain morphology effect on sheet metal formability", *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, **235**(8), 1937-1951. https://doi.org/10.1177/14644207211024686.

Habibi, M., Ghazanfari, A., Assempour, A., Naghdabadi, R. and Hashemi, R. (2017), "Determination of forming limit diagram using two modified finite element models", *Mech. Eng.*, **48**(4), 141-144. https://doi.org/10.22060/MEJ.2016.664.

Habibi, M., Hashemabadi, D. and Safarpour, H. (2019a), "Vibration analysis of a high-speed rotating GPLRC nanostructure coupled with a piezoelectric actuator", *Eur. Phys. J. Plus*, **134**(6), 307. https://doi.org/10.1140/epjp/i2019-12742-7.

Habibi, M., Hashemi, R., Ghazanfari, A., Naghdabadi, R. and Assempour, A. (2018a), "Forming limit diagrams by including the M–K model in finite element simulation considering the effect of bending", *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. **232**(8), 625-636.

Habibi, M., Hashemi, R., Sadeghi, E., Fazaeli, A., Ghazanfari, A. and Lashini, H. (2016), "Enhancing the mechanical properties and formability of low carbon steel with dual-phase microstructures", *J. Mater. Eng. Perform.*, **25**(2), 382-389. https://doi.org/10.1007/s11665-016-1882-1.

Habibi, M., Hashemi, R., Tafti, M.F. and Assempour, A. (2018b), "Experimental investigation of mechanical properties, formability and forming limit diagrams for tailor-welded blanks produced by friction stir welding", *J. Manuf. Pr.*, **31**, 310-323. https://doi.org/10.1016/j.jmapro.2017.11.009.

Habibi, M., Mohammadgholiha, M. and Safarpour, H. (2019b), "Wave propagation characteristics of the electrically GNP-reinforced nanocomposite cylindrical shell", *J. Brazil. Soc. Mech. Sci. Eng.*, **41**(5), 221. https://doi.org/10.1007/s40430-019-1715-x.

Habibi, M., Mohammadi, A., Safarpour, H. and Ghadiri, M. (2019c), "Effect of porosity on buckling and vibrational characteristics of the imperfect GPLRC composite nanoshell", *Mech. Based Des. Struct.*, 1-30. https://doi.org/10.1080/15397734.2019.1701490.

Habibi, M., Mohammadi, A., Safarpour, H., Shavalipour, A. and Ghadiri, M. (2019d), "Wave propagation analysis of the laminated cylindrical nanoshell coupled with a piezoelectric actuator", *Mech. Based Des. Struct.*, 1-19. https://doi.org/10.1080/15397734.2019.1697932.

Habibi, M., Safarpour, M. and Safarpour, H. (2020), "Vibrational characteristics of a FG-GPLRC viscoelastic thick annular plate using fourth-order Runge-Kutta and GDQ methods", *Mech. Based Des. Struct.*, 1-22. https://doi.org/10.1080/15397734.2020.1779086.

Habibi, M., Taghdir, A. and Safarpour, H. (2019e), "Stability analysis of an electrically cylindrical nanoshell reinforced with graphene nanoplatelets", *Compos. Part B Eng.*, **175**, 107125. https://doi.org/10.1016/j.compositesb.2019.107125.

Hashemi, H.R., Alizadeh, A.a., Oyarhossein, M.A., Shavalipour, A., Makkiabadi, M. and Habibi, M. (2019), "Influence of imperfection on amplitude and resonance frequency of a reinforcement compositionally graded nanostructure", *Waves Random Complex Med.*, 1-27. https://doi.org/10.1080/17455030.2019.1662968.

He, X., Ding, J., Habibi, M., Safarpour, H. and Safarpour, M. (2021), "Non-polynomial framework for bending responses of the multi-scale hybrid laminated nanocomposite reinforced circular/annular plate", *Thin Wall. Struct.*, **166**, 108019. https://doi.org/10.1016/j.tws.2021.108019.

Huang, S., Zong, G., Xu, N., Wang, H. and Zhao, X. (2024), "Adaptive dynamic surface control of MIMO nonlinear systems: A hybrid event triggering mechanism", *Int. J. Adapt. Control Signal Pr.*, **38**(2), 437-454. https://doi.org/10.1002/acs.3708.

Huang, X., Hao, H., Oslub, K., Habibi, M. and Tounsi, A. (2021), "Dynamic stability/instability simulation of the rotary size-dependent functionally graded microsystem", *Eng. Comput.*, 1-17. https://doi.org/10.1007/s00366-021-01399-3.

Imzegouan, C. (2019), "Stability for Markovian switching stochastic neural networks with infinite delay driven by Lévy noise", *Int. J. Dyn. Control*, **7**(2), 547-556. https://doi.org/10.1007/s40435-018-0451-x.

Kong, F., Dong, F., Duan, M., Habibi, M., Safarpour, H. and Tounsi, A. (2022), "On the vibrations of the Electrorheological sandwich disk with composite face sheets considering pre and post-yield regions", *Thin Wall. Struct.*, **179**, 109631. https://doi.org/10.1016/j.tws.2022.109631.

Li, J., Tang, F. and Habibi, M. (2020a), "Bi-directional thermal buckling and resonance frequency characteristics of a GNP-reinforced composite nanostructure", *Eng. Comput.*, 1-22. https://doi.org/10.1007/s00366-020-01110-y.

Li, X., Li, M., Habibi, M., Najaafi, N. and Safarpour, H. (2023), "Optimization of hybrid energy management system based on high-energy solid-state lithium batteries and reversible fuel cells", *Energy*, **283**, 128454. https://doi.org/10.1016/j.energy.2023.128454.

Li, Y., Deng, F., Xie, F. and Jiao, L. (2018), "Robust exponential stability of uncertain fuzzy stochastic neutral neural networks with mixed time-varying delays", *Int. J. Innovative Comput., Inf. Control*. **14**(2), 615-627.

Li, Y., Li, S., Guo, K., Fang, X. and Habibi, M. (2020b), "On the modeling of bending responses of graphene-reinforced higher order annular plate via two-dimensional continuum mechanics approach", *Eng. Comput.*, 1-22. https://doi.org/10.1007/s00366-020-01166-w.

Lin, S., Zhang, J. and Qiu, C. (2023), "Asymptotic analysis for one-stage stochastic linear complementarity problems and applications", *Mathematics*, **11**(2), 482. https://doi.org/10.3390/math11020482.

Liu, H., Shen, S., Oslub, K., Habibi, M. and Safarpour, H. (2021a), "Amplitude motion and frequency simulation of a composite viscoelastic microsystem within modified couple stress elasticity", *Eng. Comput.*, 1-15. https://doi.org/10.1007/s00366-021-01316-8.

Liu, H., Zhao, Y., Pishbin, M., Habibi, M., Bashir, M. and Issakhov, A. (2021b), "A comprehensive mathematical simulation of the composite size-dependent rotary 3D microsystem via two-dimensional generalized differential quadrature method", *Eng. Comput.*, 1-16. https://doi.org/10.1007/s00366-021-01419-2.

Liu, S., Wang, H., Liu, Y., Xu, N. and Zhao, X. (2024), "Sliding-mode surface-based adaptive optimal nonzero-sum games for saturated nonlinear multi-player systems with identifier-critic networks", *Neurocomputing*, **584**, 127575. https://doi.org/10.1016/j.neucom.2024.127575.

Liu, X., Lou, S. and Dai, W. (2023), "Further results on "System identification of nonlinear state-space models", *Automatica*, **148**, 110760. https://doi.org/10.1016/j.automatica.2022.110760.

Liu, Y., Wang, Z. and Liu, X. (2006), "On global exponential stability of generalized stochastic neural networks with mixed time-delays", *Neurocomputing*, **70**(1), 314-326. https://doi.org/10.1016/j.neucom.2006.01.031.

Liu, Z., Su, S., Xi, D. and Habibi, M. (2020a), "Vibrational responses of a MHC viscoelastic thick annular plate in thermal environment using GDQ method", *Mech. Based Des. Struct.*, 1-26. https://doi.org/10.1080/15397734.2020.1784201.

Liu, Z., Wu, X., Yu, M. and Habibi, M. (2020b), "Large-amplitude dynamical behavior of multilayer graphene platelets reinforced nanocomposite annular plate under thermo-mechanical loadings", *Mech. Based Des. Struct.*, 1-25. https://doi.org/10.1080/15397734.2020.1815544.

Lori, E.S., Ebrahimi, F., Supeni, E.E.B., Habibi, M. and Safarpour, H. (2020), "The critical voltage of a GPL-reinforced composite microdisk covered with piezoelectric layer", *Eng. Comput.*, 1-20. https://doi.org/10.1007/s00366-020-01004-z.

Lu, L., Liao, K., Habibi, M., Safarpour, H. and Ali, H.E. (2023a). "Numerical methods to predict aero thermally induced vibrations of a curved pipe structure reinforced by GPLs", *Structures*, **55**, 1607-1621. https://doi.org/10.1016/j.istruc.2023.06.105.

Lu, S., Li, S., Habibi, M. and Safarpour, H. (2023b), "Improving the thermo-electro-mechanical responses of MEMS resonant accelerometers via a novel multi-layer perceptron neural network", *Measurement*, 113168. https://doi.org/10.1016/j.measurement.2023.113168.

Ma, B., Chen, K.-y., Habibi, M. and Albaijan, I. (2023), "Static/dynamic analyses of sandwich micro-plate based on modified strain gradient theory", *Mech. Adv. Mater. Struct.*, 1-8. https://doi.org/10.1080/15376494.2023.2219453.

Moayedi, H., Aliakbarlou, H., Jebeli, M., Noormohammadiarani, O., Habibi, M., Safarpour, H. and Foong, L. (2020a), "Thermal buckling responses of a graphene reinforced composite micropanel structure", *Int. J. Appl. Mech.*, **12**(1), 2050010. https://doi.org/10.1142/S1758825120500106.

Moayedi, H., Ebrahimi, F., Habibi, M., Safarpour, H. and Foong, L.K. (2020b), "Application of nonlocal strain–stress gradient theory and GDQEM for thermo-vibration responses of a laminated composite nanoshell", *Eng. Comput.*, 1-16. https://doi.org/10.1007/s00366-020-01002-1.

Moayedi, H., Habibi, M., Safarpour, H., Safarpour, M. and Foong, L. (2019), "Buckling and frequency responses of a graphene nanoplatelet reinforced composite microdisk", *Int. J. Appl. Mech.*, **11**(10), 1950102. https://doi.org/10.1142/S1758825119501023.

Mohammadgholiha, M., Shokrgozar, A., Habibi, M. and Safarpour, H. (2019), "Buckling and frequency analysis of the nonlocal strain–stress gradient shell reinforced with graphene nanoplatelets", *J. Vib. Control*, **25**(19-20), 2627-2640. https://doi.org/10.1177/1077546319863251.

Mohammadi, A., Lashini, H., Habibi, M. and Safarpour, H. (2019), "Influence of viscoelastic foundation on dynamic behaviour of the double walled cylindrical inhomogeneous micro shell using MCST and with the aid of GDQM", *J. Solid Mech.*, **11**(2), 440-453. https://doi.org/10.22034/JSM.2019.665264.

Najaafi, N., Jamali, M., Habibi, M., Sadeghi, S., Jung, D.w. and Nabipour, N. (2020), "Dynamic instability responses of the substructure living biological cells in the cytoplasm environment using stress-strain size-dependent theory", *J. Biomol. Struct. Dyn.*, 1-12. https://doi.org/10.1080/07391102.2020.1751297.

Oyarhossein, M.A., Alizadeh, A.a., Habibi, M., Makkiabadi, M., Daman, M., Safarpour, H. and Jung, D.W. (2020), "Dynamic response of the nonlocal strain-stress gradient in laminated polymer composites microtubes", *Sci. Rep.*, **10**(1), 1-19. https://doi.org/10.1038/s41598-020-61855-w.

Peng, S., Habibi, M. and Pourjabari, A. (2023), "Generalized differential quadrature element solution, swarm, and GA optimization technique to obtain the optimum frequency of the laminated rotary nanostructure", *Eng. Anal. Bound. Elem.*, **151** 101-114. https://doi.org/10.1016/j.enganabound.2023.02.052.

Pourjabari, A., Hajilak, Z.E., Mohammadi, A., Habibi, M. and Safarpour, H. (2019), "Effect of porosity on free and forced vibration characteristics of the GPL reinforcement composite nanostructures", *Comput. Math. Appl.*, **77**(10), 2608-2626. https://doi.org/10.1016/j.camwa.2018.12.041.

Rakkiyappan, R. and Balasubramaniam, P. (2010), "Delay-probability-distribution-dependent stability of uncertain stochastic genetic regulatory networks with mixed time-varying delays: An LMI approach", *Nonlinear Anal. Hybrid Syst.*, **4**(3), 600-607. https://doi.org/10.1016/j.nahs.2010.03.007.

Sabzevari, F., Amelirad, O., Moradi, Z. and Habibi, M. (2023), "Artificial intelligence evaluation of COVID-19 restrictions and speech therapy effects on the autistic children's behavior", *Sci. Rep.*, **13**(1), 4312. https://doi.org/10.1038/s41598-022-25902-y.

Safarpour, H., Ghanizadeh, S.A. and Habibi, M. (2018), "Wave propagation characteristics of a cylindrical laminated composite nanoshell in thermal environment based on the nonlocal strain gradient theory", *Eur. Phys. J. Plus*, **133**(12), 532. https://doi.org/10.1140/epjp/i2018-12385-2.

Safarpour, H., Hajilak, Z.E. and Habibi, M. (2019a), "A size-dependent exact theory for thermal buckling, free and forced vibration analysis of temperature dependent FG multilayer GPLRC composite nanostructures restring on elastic foundation", *Int. J. Mech. Mater. Des.*, **15**(3), 569-583. https://doi.org/10.1007/s10999-018-9431-8

Safarpour, H., Pourghader, J. and Habibi, M. (2019b), "Influence of spring-mass systems on frequency behavior and critical voltage of a high-speed rotating cantilever cylindrical three-dimensional shell coupled with piezoelectric actuator", *J. Vib. Control*, **25**(9), 1543-1557. https://doi.org/10.1177/1077546319828465.

Safarpour, M., Ebrahimi, F., Habibi, M. and Safarpour, H. (2020), "On the nonlinear dynamics of a multi-scale hybrid nanocomposite disk", *Eng. Comput.*, 1-20. https://doi.org/10.1007/s00366-020-00949-5.

Shao, Y., Zhao, Y., Gao, J. and Habibi, M. (2021), "Energy absorption of the strengthened viscoelastic multi-curved composite panel under friction force", *Arch. Civil Mech. Eng.*, **21**(4), 1-29. https://doi.org/10.1007/s43452-021-00279-3.

Shariati, A., Habibi, M., Tounsi, A., Safarpour, H. and Safa, M. (2020a), "Application of exact continuum size-dependent theory for stability and frequency analysis of a curved cantilevered microtubule by considering viscoelastic properties", *Eng. Comput.*, 1-20. https://doi.org/10.1007/s00366-020-01024-9.

Shariati, A., Mohammad-Sedighi, H., Żur, K.K., Habibi, M. and Safa, M. (2020b), "On the vibrations and stability of moving viscoelastic axially functionally graded nanobeams", *Materials*, **13**(7), 1707. https://doi.org/10.3390/ma13071707.

Shariati, A., Mohammad-Sedighi, H., Żur, K.K., Habibi, M. and Safa, M. (2020c), "Stability and dynamics of viscoelastic moving rayleigh beams with an asymmetrical distribution of material parameters", *Symmetry*, **12**(4), 586. https://doi.org/10.3390/sym12040586.

Shariati, M., Kamyab, H., Habibi, M., Ahmadi, S., Naghipour, M., Gorjinezhad, F., Mohammadirad, S. and Aminian, A. (2023), "Sulfuric acid resistance of concrete containing coal waste as a partial substitute for fine and coarse aggregates", *Fuel*, **348**, 128311. https://doi.org/10.1016/j.fuel.2023.128311.

Shokrgozar, A., Safarpour, H. and Habibi, M. (2020), "Influence of system parameters on buckling and frequency analysis of a spinning cantilever cylindrical 3D shell coupled with piezoelectric actuator", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **234**(2), 512-529. https://doi.org/10.1177/0954406219883312.

Singh, V. (2004), "Robust stability of cellular neural networks with delay: linear matrix inequality approach", *IEEE Proceedings of the Control Theory and Applications*, **151**(1), 125-129. https://doi.org/10.1049/ip-cta:20040091.

Song, Y., Sun, W. and Jiang, F. (2016), "Mean-square exponential input-to-state stability for neutral stochastic neural networks with mixed delays", *Neurocomputing*, **205**, 195-203. https://doi.org/10.1016/j.neucom.2016.03.048.

Tang, J., Wu, S., Habibi, M., Safarpour, M. and Ali, H.E. (2023), “Flutter analysis of multi-directional functionally graded sector poroelastic disks”, *Aerosp. Sci. Technol.*, **140**, 108481. https://doi.org/10.1016/j.ast.2023.108481.

Tang, Q., Qu, S., Zhang, C., Tu, Z. and Cao, Y. (2024), “Effects of impulse on prescribed-time synchronization of switching complex networks”, *Neural Netw.*, **174**, 106248. https://doi.org/10.1016/j.neunet.2024.106248.

Tian, J., Wang, B., Guo, R., Wang, Z., Cao, K. and Wang, X. (2022), “Adversarial attacks and defenses for deep-learning-based unmanned aerial vehicles”, *IEEE Internet Things J.*, **9**(22), 22399-22409. https://doi.org/10.1109/JIOT.2021.3111024.

Wang, F., Ma, M. and Zhang, X. (2024a), “Study on a portable electrode used to detect the fatigue of tower crane drivers in real construction environment”, *IEEE T. Instrum. Measure.*, **73**, 1-14. https://doi.org/10.1109/TIM.2024.3353274.

Wang, W., Liang, J., Liu, M., Ding, L. and Zeng, H. (2024b), “Novel robust stability criteria for Lur’e systems with time-varying delay”, *Mathematics*, **12**(4), 583. https://doi.org/10.3390/math12040583.

Wang, W., Zeng, H.B., Teo, K.L. and Chen, Y.J. (2023a), “Relaxed stability criteria of time-varying delay systems via delay-derivative-dependent slack matrices”, *J. Franklin Inst.*, **360**(9), 6099-6109. https://doi.org/10.1016/j.jfranklin.2023.04.019.

Wang, Y., Jia, Q., Deng, T., Habibi, M., Al-Kikani, S. and Ali, H.E. (2023b), “Wave propagation analysis of the ball in the handball’s game”, *Struct. Eng. Mech.*, **85**(6), 729-742. https://doi.org/10.12989/sem.2023.85.6.729.

Wang, Z., Yu, S., Xiao, Z. and Habibi, M. (2020), “Frequency and buckling responses of a high-speed rotating fiber metal laminated cantilevered microdisk”, *Mech. Adv. Mater. Struct.*, 1-14. https://doi.org/10.1080/15376494.2020.1824284.

Wu, F., Hu, S. and Huang, C. (2010), “Robustness of general decay stability of nonlinear neutral stochastic functional differential equations with infinite delay”, *Syst. Control Lett.*, **59**(3), 195-202. https://doi.org/10.1016/j.sysconle.2010.01.004.

Wu, J. and Habibi, M. (2021), “Dynamic simulation of the ultra-fast-rotating sandwich cantilever disk via finite element and semi-numerical methods”, *Eng. Comput.*, 1-17. https://doi.org/10.1007/s00366-021-01396-6.

Wu, X., Ding, S., Xu, N., Niu, B. and Zhao, X. (2023), “Periodic event-triggered bipartite containment control for nonlinear multi-agent systems with input delay”, *Int. J. Syst. Sci.*, 1-15. https://doi.org/10.1080/00207721.2024.2328780.

Xiang, J., Lai, Y., Moradi, Z. and Khorami, M. (2023), “Wave propagation phenomenon of functionally graded graphene oxide powder-strengthened nanocomposite curved beam”, *Solid State Commun.*, 115193. https://doi.org/10.1016/j.ssc.2023.115193.

Xiong, Q.M., Chen, Z., Huang, J.T., Zhang, M., Song, H., Hou, X.F., Li, X.B. and Feng, Z.J. (2020), “Preparation, structure and mechanical properties of Sialon ceramics by transition metal-catalyzed nitriding reaction”, *Rare Metals*, **39**(5), 589-596. https://doi.org/10.1007/s12598-020-01385-6.

Xu, B. and Guo, Y. (2022), “A novel DVL calibration method based on robust invariant extended Kalman filter”, *IEEE T. Vehicul. Technol.*, **71**(9), 9422-9434. https://doi.org/10.1109/TVT.2022.3182017.

Yang, C., Su, C., Hu, H., Habibi, M., Safarpour, H. and Khadimallah, M.A. (2023), “Performance optimization of photovoltaic and solar cells via a hybrid and efficient chimp algorithm”, *Solar Energy*, **253**, 343-359. https://doi.org/10.1016/j.solener.2023.02.036.

Yang, M., Han, W., Song, Y., Wang, Y. and Yang, S. (2024), “Data-model fusion driven intelligent rapid response design of underwater gliders”, *Adv. Eng. Inform.*, **61**, 102569. https://doi.org/10.1016/j.aei.2024.102569.

Yao, Y., Zhao, B., Zhao, J., Shu, F., Wu, Y. and Cheng, X. (2024), “Anti-jamming technique for IRS aided JRC system in mobile vehicular networks”, *IEEE T. Intell. Transp. Syst.*, 1-11. https://doi.org/10.1109/TITS.2024.3384038.

Yu, J., Lu, L., Chen, Y., Zhu, Y. and Kong, L. (2021), “An Indirect Eavesdropping Attack of Keystrokes on Touch Screen through Acoustic Sensing”, *IEEE T. Mobile Comput.*, **20**(2), 337-351.

https://doi.org/10.1109/TMC.2019.2947468.

Zare, R., Najaafi, N., Habibi, M., Ebrahimi, F. and Safarpour, H. (2020), "Influence of imperfection on the smart control frequency characteristics of a cylindrical sensor-actuator GPLRC cylindrical shell using a proportional-derivative smart controller", *Smart Struct. Syst.*, **26**(4), 469-480. https://doi.org/10.12989/sss.2020.26.4.469.

Zhang, H., Dong, M., Wang, Y. and Sun, N. (2010), "Stochastic stability analysis of neutral-type impulsive neural networks with mixed time-varying delays and Markovian jumping", *Neurocomputing*, **73**(13), 2689-2695. https://doi.org/10.1016/j.neucom.2010.04.016.

Zhang, H., Qiu, Z. and Xiong, L. (2019), "Stochastic stability criterion of neutral-type neural networks with additive time-varying delay and uncertain semi-Markov jump", *Neurocomputing*, **333**, 395-406. https://doi.org/10.1016/j.neucom.2018.12.028.

Zhang, H., Zou, Q., Ju, Y., Song, C. and Chen, D. (2022), "Distance-based support vector machine to predict DNA N6- methyladenine modification", *Curr. Bioinform.*, **17**(5), 473-482. https://doi.org/10.2174/1574893617666220404145517.

Zhang, Q., Zou, X., Wang, Y. and Habibi, M. (2023a), "Study on photocatalytic, electric, and sensing behavior of Co-and Ag-codoped tin dioxide (SnO2) nano particles", *Mater. Sci. Eng. B*, **296**, 116687. https://doi.org/10.1016/j.mseb.2023.116687.

Zhang, S., Lai, Y., Chen, K., Habibi, M., Khorami, M. and Haider Mussa, Z. (2023b), "Influence of MWCNT's waviness and aggregation factors on wave dispersion response of MWCNT-strengthened nanocomposite curved beam", *Structures*, **53**, 1239-1249. https://doi.org/10.1016/j.istruc.2023.04.024.

Zhang, W. and Wang, L. (2012), "Robust stochastic stability analysis for uncertain neutral-type delayed neural networks driven by wiener process", *J. Appl. Math.*, 829594. https://doi.org/10.1155/2012/829594.

Zhang, Y., Wang, Z., Tazeddinova, D., Ebrahimi, F., Habibi, M. and Safarpour, H. (2021), "Enhancing active vibration control performances in a smart rotary sandwich thick nanostructure conveying viscous fluid flow by a PD controller", *Waves Random Complex Med.*, 1-24. https://doi.org/10.1080/17455030.2021.1948627.

Zhao, H., Li, C., Fu, Y., Oyarhossein, M.A., Habibi, M. and Safarpour, H. (2023), "Quasi-static indentation, low-velocity impact, and resonance responses of the laminated double-curved panel considering various boundary conditions", *Thin Wall. Struct.*, **183**, 110360. https://doi.org/10.1016/j.tws.2022.110360.

Zheng, C.D., Lv, X., Liang, W. and Wang, Z. (2015), "Robust stochastic convergence and stability of neutral-type neural networks with Markovian jump and mixed delays", *Int. J. Adapt. Control Signal Pr.*, **29**(2), 158-179. https://doi.org/10.1002/acs.2461.

Zheng, W., Liu, J., Oyarhossein, M.A., Safarpour, H. and Habibi, M. (2023), "Prediction of nth-order derivatives for vibration responses of a sandwich shell composed of a magnetorheological core and composite face layers", *Eng. Anal. Bound. Elem.*, **146**, 170-183. https://doi.org/10.1016/j.enganabound.2022.10.019.

Zhou, C., Zhao, Y., Zhang, J., Fang, Y. and Habibi, M. (2020), "Vibrational characteristics of multi-phase nanocomposite reinforced circular/annular system", *Adv. Nano Res.*, **9**(4), 295-307. https://doi.org/10.12989/anr.2020.9.4.295.

Zhu, L., Ren, H., Habibi, M., Mohammed, K.J. and Khadimallah, M.A. (2022), "Predicting the environmental economic dispatch problem for reducing waste nonrenewable materials via an innovative constraint multi-objective Chimp Optimization Algorithm", *J. Clean. Prod.*, 132697. https://doi.org/10.1016/j.jclepro.2022.132697.

Zhu, Q. and Cao, J. (2010), "Stability analysis for stochastic neural networks of neutral type with both Markovian jump parameters and mixed time delays", *Neurocomputing*, **73**(13), 2671-2680. https://doi.org/10.1016/j.neucom.2010.05.002.

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