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LDI NN auxiliary modeling and control design for nonlinear systems

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Abstract. This study investigates an effective approach to stabilize nonlinear systems. To ensure the asymptotic nonlinear stability in nonlinear discrete-time systems, the present study presents controller for an EBA (Evolved Bat Algorithm) NN (fuzzy neural network) in the algorithm. In fuzzy evolved NN modeling, the auxiliary circuit with high frequency LDI (linear differential inclusions) and NN model representation is developed for the nonlinear arbitrary dynamics. An example is utilized to demonstrate the system more robust compared with traditional control systems.

Keywords: artificial intelligence; fuzzy theory; intelligent algorithm; LDI; NN controller

1. Introduction

In the two decades to three decades, there have been great deals of active control, implementation and semi-development in research- hybrid and active structures (for example, Kmet 2004, Connor 2003, Adley and Kim 2004, Kim and Adeli 2004, has put forward several control strategies, such as Chen *et al*. (2011), Chen (2011), Jiang and Adeli (2005, 2006), current literatures (Akhavan Alavi *et al*. 2021, Taherifar *et al*. 2020, Lu *et al*. 2022, Mazloom *et al*. 2020, Ghamkhar *et al*. 2022, Ozdemir *et al*. 2021) as well as sliding mode control. However, most research focuses on those applications of those linear classical control theory, such as secondary regulator linear feedback control algorithm and linear secondary control Gaussian algorithm (Ulusoy *et al*. 2020, Hsiao *et al*. 2005, Chen 2005, Chen *et al*. 2009, Chen 2009, Maciejowski 1989, Moore 1981, Stein and Athans 1987, Hung *et al*. 2019). Fuzzy control and neural network (NN) control have been subjects of intense research among them.

The region of metaheuristic advancement calculations has been drawing in analysts for a long time. These calculations have worked in ability to investigate an extensive area of the arrangement space, are computationally strong, productive and can dodge untimely combination. They have been broadly tried and connected on numerous hard advancement issues where customary registering strategies perform unsuitably (Lv *et al*. 2022, Cao *et al*. 2022, Liu *et al*. 2022, Wu *et al*. 2020, Zheng *et al*. 2021, Zheng *et al*. 2022, Zhong *et al*. 2022, Zheng *et al*. 2022). They are equipped for settling general N-dimensional, straight, nonlinear and complex worldwide enhancement issues. One of the most recent participants in this field is the Bat calculation which depends on the echolocation conduct of bats. It has been demonstrated to have great intermingling properties on various benchmark works and appears to be encouraging for managing improvement issues. The point of this paper is to give a study of the best in class on Bat calculation. A succinct exertion has been made so the peruses get a fast understanding into a portion of the applications whereupon bat calculation has been connected till date in particular fields of science and designing. A portion of the variations of the bat calculation as revealed in the writing have additionally been examined.

Amid the previous quite a while, fuzzy principle-based displaying has turned into a functioning examination field as a result of its one of a kind merits in illuminating complex nonlinear framework ID and control issues. In endeavor to acquire greater adaptability and increasingly powerful capacity of taking care of and handling vulnerabilities in entangled and not well characterized frameworks, which is proposed a semantic methodology as the model of human reasoning that brought the fluffiness into frameworks hypothesis. In contrast to customary demonstrating, fluffy standard based displaying is a multimodel approach basically in which singular guidelines are consolidated for depicting the worldwide conduct of these frameworks. Likewise, the control calculation has been improved for the application in robot controller.

Neural systems have been made out of the components working by parallel. These straightforward components have been motivated by sensory natural systems (Wang *et al*. 2022, Zhao *et al*. 2022, Meng *et al*. 2022, Li *et al*. 2022, Meng *et al*. 2021). At that point, we can prepare a neural system to talk to a special capacity by modifying these loads in between components. Since the structure of a fuzzy

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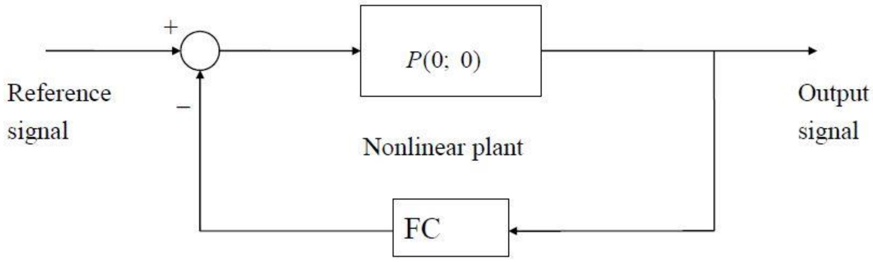


Fig. 1 Closed-loop nonlinear system $P(C;\ 0)$

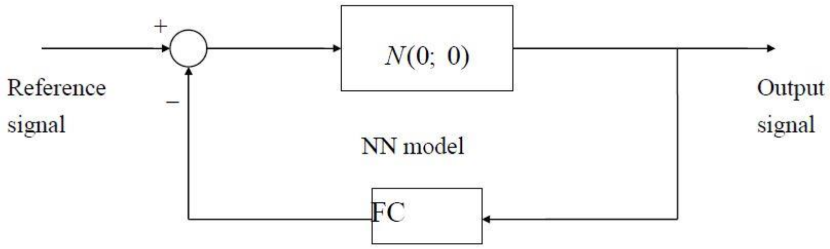


Fig. 2 Closed-loop NN system $N(C;\ 0)$

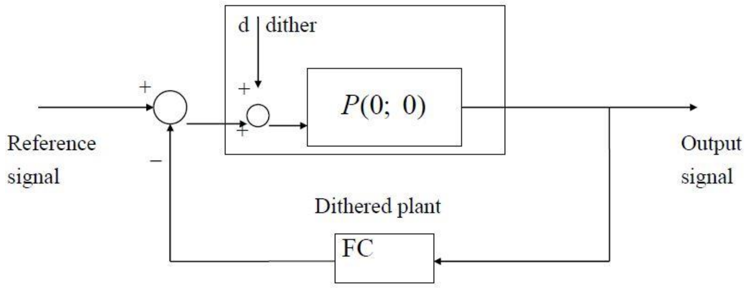


Fig. 3 Closed-loop dithered system $\boldsymbol{P(C;\ d)}$

controller is more straightforward than that of a regular PID controller, it has been proposed as an elective way to deal with control strategies for complex control frameworks. Lamentably, no efficient strategy has yet been created to modify the parameters of the controller with the end goal that the shut circle framework is steady. Thus, this paper proposes another way to deal with this issue. Our approach is to surmise a nonlinear plant with a multilayer perceptron of which the exchange capacities are of the sigmoid class symmetric to the beginning in this examination. At that point, the elements of this NN show is changed over into LDI portrayal. In light of this methodology, if the shut circle framework can't be balanced out, a vacillate, as an assistant of the controller, is infused into the nonlinear framework.

It has been for quite some time realized that the infusion of a high frequency circuit, known as a vacillate, into a nonlinear plant might improve its execution. Better execution is seen as less contortion in the framework yield, enlarged steadiness, and extinguishing of cutoff cycles just as hop marvels. A thorough investigation of solidness in a general nonlinear framework with a vacillate control was given in Adeli and Jiang (2006). It was demonstrated that the direction of a vacillated framework can be anticipated thoroughly by setting up that of its relating model– the casual model (which relies upon the parameters of vacillate), gave the vacillate has an adequately high recurrence. This reality empowers us to get a thorough forecast of the strength of the shut circle vacillated framework by setting up the soundness of the shut circle NN loosened up framework. Chen *et al*. (2009) also built fuzzy control for multiple nonlinear time-delay systems and robust fuzzy controller design for dithered system. He provided the systematic and simplified design and analysis for the control system of the dither. This study might be viewed as proposing an alternative of the approach to the stabilization of fuzzy-neural systems by dithers.

2. Preliminary notations and definitions

The following notations will be used throughout this paper.

$\boldsymbol{P(0;\ 0)}$	nonlinear plant
$N(0;\ 0)$	NN model of $P(0;\ 0)$
$P(0;\ d)$	dithered plant
$P_R(0;\ 0)$	relaxed model of $P(0;\ d)$
$N_R(0;\ 0)$	NN relaxed model of $P_R(0;\ 0)$
$P(C;\ 0)$	closed-loop nonlinear system (see Fig. 1)
$N(C;\ 0)$	closed-loop NN system (see Fig. 2)
$P(C;\ d)$	closed-loop dithered system (see Fig. 3)
$P_R(C;\ 0)$	closed-loop relaxed system (see Fig. 4)
$N_R(C;\ 0)$	closed-loop NN relaxed system (see Fig. 5)

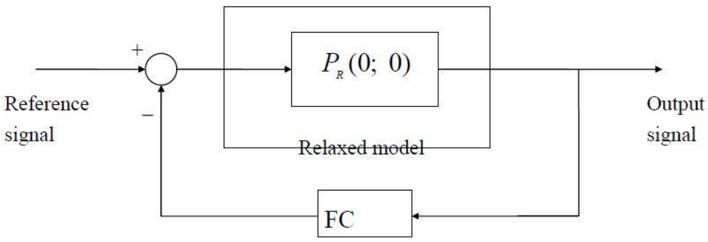


Fig. 4 Closed-loop relaxed system $\boldsymbol{P_R(C;\ 0)}$

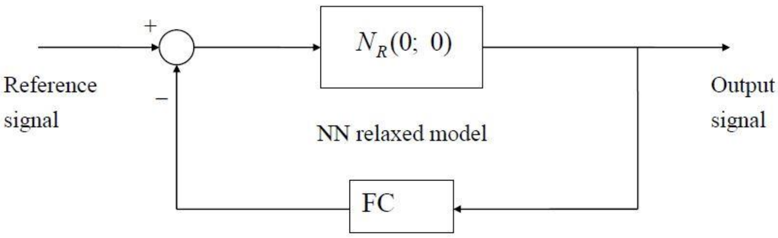


Fig. 5 Closed-loop NN relaxed system $\boldsymbol{N_R(C;\ 0)}$

3. System description

Consider a nonlinear plant $P(0;\ 0)$ described by the following equation

$$X(k+1) = f\big(X(k), U(k)\big), \tag{1}$$

where $U(k)$ is the input vector, $X(K)$ is the state vector, and $f(.)$ is a vector-valued function which corresponds to those assumptions of boundedness which is derived in Tanaka *et al*. (1996).

In this section, a NN display is first settled to rough a nonlinear plant. At that point, these elements of the NN show is changed over into LDI portrayal. In this manner, a fuzzy controller is intended to balance out the nonlinear framework.

3.1 Neural-Network (NN) Models

An NN model with S layers and each layer has R^e (e = 1, 2, ..., S) neurons is established to approximate (1), where $x(k) \sim x(k-m+1)$ are the state and $u(k) \sim u(k-n+1)$ are the input implied transfer function vector of the eth layer stands

$$\Psi^e(v) \equiv [T_1(v) \quad \cdots \quad T_{R^e}(v)]^T, \quad e = 1,2,\ldots,S$$

where $T_r(v)$ $(r = 1,2,\ldots,R^e)$ are the transfering functions which are associated with $\Psi^e(v)$ and thus the output is

$$x(k+1) = \Psi^S(W^S \times \Psi^{S-1}(W^{S-1} \times \Psi^{S-2}(\cdots\cdots \cdot \Psi^2(W^2 \times \Psi^1(W^1 \times Z(k))) \cdots\cdots))), \tag{2}$$

where the linear differential inclusion (LDI) system described as

$$A\big(a(k)\big) = \sum_{i=1}^{l} h_i\big(a(k)\big)A_i \quad \text{and} \quad y(k+1) = A(a(k))y(k), \tag{3}$$

Then, we can obtain the following equations based on the method of interpolation and analysis above

$$x(k+1) = \sum_{v^S} \cdots \sum_{v^1} h^S_{v^S} \cdots h^1_{v^1} G(v^S, \Psi^S)W^S \cdots G(v^1, \Psi^1)W^1 y\,(k) \tag{4}$$

where

$$\sum_{v^e} h^e_{v^e} = \sum_{j_1^e=1}^{2} \cdots \sum_{j_{R^e}^e=1}^{2} h^e_{j_1^e} \cdots h^e_{j_{R^e}^e}, h^e_1, h^e_2 \in [0,1], \quad \sum_{j_r^e=1}^{2} h^e_{j_r^e} = 1, \tag{5}$$

which can be rewritten as

$$X(k+1) = \sum_{i=1}^{l} h_i(k)\{A_i(W,\Psi)X(k) + B_i(W,\Psi)U(k)\} \tag{6}$$

3.2 Fuzzy controllers

We are introducing a Takagi-Sugeno (T-S) fuzzy controller described by rules

$$\text{IF} \quad x_m(k) \text{ is } M_{jm} \quad \text{THEN} \quad u(k) = -F_j X(k), \tag{7}$$

where

$$u(k) = -\sum_{j=1}^{\delta} \bar{h}_j(k)F_j X(k), \tag{8}$$

and

$$X(k+1) = \sum_{i}^{l}\sum_{j=1}^{\delta} h_i(k)\,\bar{h}_j(k)\{A_i(W,\Psi) - B_i(W,\Psi)F_j\}X(k). \tag{9}$$

As indicated by the Lyapunov approach, the accompanying lemma is given to ensure the asymptotic soundness of the above shut circle NN framework. Given a real number $\gamma > 0$, it is said that the exogenous input is locally attenuated by γ if there exists a neighborhood U of $\boldsymbol{x}(k) = 0$ such that to every positive integer N and to every $\boldsymbol{b}(k) \in \ell_2([0,N],\Re^r)$ in which these state trajectories of the nonlinear closed-loop system (10) starting from $\boldsymbol{x}(0) = 0$ remains in U for all $k \in [0,N]$, the response $\boldsymbol{x}(k) \in \ell_2([0,N],\Re^m)$ satisfies

$$\sum_{k=0}^{N} \boldsymbol{x}(k)^T \boldsymbol{Q} \boldsymbol{x}(k) < \boldsymbol{x}(0)^T \boldsymbol{P} \boldsymbol{x}(0) + \gamma^2 \sum_{k=0}^{N} \boldsymbol{b}(k)^T \boldsymbol{b}(k) \; \forall N \tag{10}$$

where $\boldsymbol{Q}$ is a definite positive weighting matrix. The physical condition meaning is to find an L_2 gain smaller than or equal to a prescribed number γ (less than 1 strictly).

Lemma 3.1 (Tanaka *et al.* 1996, Chen *et al.* 2007, Yeh *et al.* 2007, Chen 2007) (9) is stable asymptotically in the large if there exists a common definite positive matrix Q such that

$$H_{ij}^T Q H_{ij} - Q < 0 \quad \text{and} \quad H_{ij} = A_i(W,\Psi) - B_i(W,\Psi)F_j \tag{11}$$

To check stability $N(C;\ 0)$, we must find a Q satisfied in (11).

According to these stability conditions addressed in Lemma 3.1, the closed-loop NN system $N(C;\ 0)$ is classified into two types.

1) Type 1: $N_1(C;\ 0)$. On the off chance that there was out a typical positive clear grid Q to fulfill the dependability conditions in Lemma 3.1, at that point the controller can balance out $N_1(C;\ 0)$.

2) Type 2: $N_2(C;\ 0)$. In the event that there doesn't exist any basic positive distinct lattice Q to fulfill the security conditions in Lemma 3.1, at that point the controller and the vacillate are at the same time acquainted with asymptotically balance out the shut circle framework when the controller can't balance out $N_2(C;\ 0)$.

Accordingly, in the rest of this paper, consideration is dedicated to the steadiness investigation of $N_2(C;\ 0)$.

4. NN relaxed model and stability analysis

In this section, we present a new approach to make $N_2(C;\ 0)$ stable without changing the designed feedback gain F_i of the fuzzy controller.

4.1 Dithered plant and relaxed model

In order to stabilize $N_2(C;\ 0)$, $d(k)$ with a finite number η, is injected to $P(0;\ 0)$ and the $P(0;\ d)$ is described as

$$X(k+1) = f\big(X(k), U(k), d(k)\big). \tag{12}$$

The calculation for building a vacillate auxiliary circuit is given as pursues: The time interim is separated into a discretionary number of equivalent subintervals. The start of the main interim, the finish of the primary interim, the second's end interim and the finish of the interim are meant by k_0, k_1, k_2 and k_η respectively. Dividing every interval (k_φ, $k_{\varphi+1}$) for $\varphi = 0,1,2,\ldots,\eta-1$ into τ subintervals, the length of the mth subinterval will be $\alpha_m(k_\varphi)\cdot(k_{\varphi+1}-k_\varphi)$ for $m = 1,\ 2,\ \ldots,\ \tau$ and the control $\beta_m(k_\varphi)$ is applied at the mth subinterval. Consequently, the reiteration recurrence, shape and abundancy of vacillate can be controlled by directing the parameters η, $\alpha_m(k_\varphi)$ and $\beta_m(k_\varphi)$.

Remark 4.1: As indicated by this calculation, we have that in the event that the vacillate is picked to be an occasional frequency circuit, at that point the parameters $\alpha_m(k)$ and $\beta_m(k)$ are independent of time.

The corresponding relaxed model $P_R(0;\ 0)$ of the $P(0;\ d)$ is defined as

$$x_R(k+1) = \sum_{m=1}^{\tau} \alpha_m(k)\, f(x_R, u, \beta_m), \tag{13}$$

in which $\alpha_m(k)$ is non-negative and satisfies the following conditions

$$0 \le \alpha_m(k) \le 1, \text{ for } m = 1, 2, \ldots, \tau, \ \sum_{m=1}^{\tau} \alpha_m(k) = 1.$$

Remark 4.2: The curve $x_R(k)$ satisfying (13) is the uniform limit of curves $x_\eta(k)$, $\eta = 1,\ 2, \ldots$, satisfying (12). In other words, as the recurrence of vacillate goes to endlessness, the direction portrayed by the vacillated plant (12) will approach that of the casual model (13). Henceforth, the casual model might be seen as the scientific model of the nonlinear plant with a vacillate of sufficiently high recurrence.

Based on Remark 4.2, if η is chosen large, then $P(0;\ d)$ is approximated by the $P_R(0;\ 0)$ and the approximation improves as η increase. Consequently, the behavior described by $P(0;\ d)$ and the behavior of $P_R(0;\ 0)$ would be made desirably closed.

4.2 NN relaxed model

Then, $N_R(0;\ 0)$ of the $P(0;\ d)$ is reconstructed. First, F_i is obtained and $N_R(C;\ 0)$ is

$$X(k+1) = \sum_{i=1}^{l} \sum_{j=1}^{\delta} h_i(\alpha_m, \beta_m) \bar{h}_j\big(X(k)\big) \{A_i(W,\Psi) - B_i(W,\Psi)F_j\} X(k), \tag{14}$$

Remark 4.3: If the frequency of injected auxiliary circuit is high, the trajectory of $N_R(C;\ 0)$ and $P(C;\ d)$ would be made as close as desired. This enables us to rigorously predict the stability of $P(C;\ d)$ by establishing $N_R(C;\ 0)$.

4.3 Stability analysis

Hereafter, we are considering the stability of $N_R(C;\ 0)$

instead of discussing the stability of $P(C;\ d)$. Hence, the stability of $N_R(C;\ 0)$ is presented in the following.

Theorem 4.1 $N_R(C;\ 0)$ is asymptotically stable in the large if there exists a common positive definite matrix Q such that

$$M_{ij}(\alpha_m,\beta_m)^T Q M_{ij}(\alpha_m,\beta_m) - Q < 0,\quad i = 1,2,\dots,l \tag{15}$$

where

$$M_{ij}(\alpha_m,\beta_m) = A_i\big(W(\alpha_m,\beta_m),\Psi(\alpha_m,\beta_m)\big) - B_i(W(\alpha_m,\beta_m),\Psi(\alpha_m,\beta_m))F_j.$$

The verification of the above hypothesis can be also inferred by following a similar system as that in the evidence of Tanaka *et al.* (1996) but with H_{ij} being replaced by $M_{ij}(\alpha_m,\beta_m)$. This proof is lengthy, so it is not repeated here.

Remark 4.4: According to Theorem 4.1, we can appropriately regulate the parameters α_m and β_m to stabilize $N_R(C;\ 0)$ by the designed fuzzy controller.

5. A numerical example

The aim of this case syudy is to synthesize a fuzzy controller with high frequency circuit injected into the following (16) and the parameters are regulated to make $P(C;\ d)$ stable.

$$x(k+1) = -1.1\cdot x(k-1) + 0.2\cdot x(k)^2\cdot u(k) \tag{16}$$

Step 1: The nonlinear plant (16) can be built by the sigmoid NN display. So as to improve the calculations, we consider a suitable NN display with two layers where the concealed layer contains three neurons and the yield layer is a solitary neuron. These networks are prepared by the backpropagation calculation utilizing a uniform contribution to the interim (-2 2). After training, the weights can be obtained as follows

$$\begin{aligned} &W_{11}^1 = -5.9556, && W_{21}^1 = 3.4560, && W_{31}^1 = 1.7898,\\ &W_{12}^1 = 0.9449, && W_{22}^1 = -0.0695, && W_{32}^1 = 0.3184,\\ &W_{13}^1 = -1.2457, && W_{23}^1 = 0.1706, && W_{33}^1 = 0.0221,\\ &W_{11}^2 = 0.9446, && W_{21}^2 = -6.4447, && W_{31}^2 = -5.7764. \end{aligned}$$

Then, the NN model can be described as

$$v_i^1 = W_{1i}^1 x(k) + W_{2i}^1 x(k-1) + W_{3i}^1 u(k),\quad i = 1,2,3 \tag{17}$$

$$v_1^2 = W_{11}^2 T_1^1(v_1^1) + W_{21}^2 T_2^1(v_2^1) + W_{31}^2 T_3^1(v_3^1), \tag{18}$$

$$x(k+1) = T_1^2(v_{11}^2), \tag{19}$$

$$T_j^1(v_j^1) = \frac{2}{1+exp\left(-\frac{v_j^1}{0.5}\right)} - 1,\quad j = 1,2,3 \tag{20}$$

According to (20), the bounding value of derivation of would be

$$g_1 = \min_v T'(v) = 0,\quad g_2 = \max_v T'(v) = 1. \tag{21}$$

Then, according to the interpolation method, (20)-(21) can be represented by (22)-(23)

$$T_j^1(v_j^1) = \big(h_{j1}^1(k)g_1 + h_{j2}^1(k)g_2\big)v_j^1,\quad j = 1,2,3 \tag{22}$$

$$x(k+1) = (h_{11}^2(k)g_1 + h_{12}^2(k)g_2)v_1^2 = \sum_{i=1}^{2} h_{1i}^2(k)g_i v_1^2, \tag{23}$$

which yields

$$x(k+1) = \sum_{i=1}^{2} h_{1i}^2(k)g_i \sum_{j=1}^{3} W_{j1}^2 T_j^1(v_j^1). \tag{24}$$

$$= \sum_{i=1}^{2} h_{1i}^2(k)g_i \sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2} h_{1j}^1(k)h_{2p}^1(k)h_{3s}^1(k)\{g_j W_{11}^2 v_1^1 + g_p W_{21}^2 v_2^1 + g_s W_{31}^2 v_3^1\}. \tag{25}$$

By plugging (17) into (24), we obtain

$$x(k+1)=\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2}h_{1i}^{2}(k)h_{1j}^{1}(k)h_{2p}^{1}(k)h_{3s}^{1}(k)\times[g_i\cdot\{g_jW_{11}^{2}W_{11}^{1}+g_pW_{21}^{2}W_{12}^{1}+g_sW_{31}^{2}W_{13}^{1}\}x(k) \\ +g_i\cdot\{g_jW_{11}^{2}W_{21}^{1}+g_pW_{21}^{2}W_{22}^{1}+g_sW_{31}^{2}W_{23}^{1}\}x(k-1) \\ +g_i\cdot\{g_jW_{11}^{2}W_{31}^{1}+g_pW_{21}^{2}W_{32}^{1}+g_sW_{31}^{2}W_{33}^{1}\}u(k)]. \tag{26}$$

The matrix representation is

$$X(k+1)=\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2}h_{1i}^{2}(k)h_{1j}^{1}(k)h_{2p}^{1}(k)h_{3s}^{1}(k)\times\{A_{ijps}X(k)+B_{ijps}u(k)\} \tag{27}$$

where

$$A_{ijps}=\begin{bmatrix} g_i\cdot\{g_jW_{11}^{2}W_{11}^{1}+g_pW_{21}^{2}W_{12}^{1}+g_sW_{31}^{2}W_{13}^{1}\} & g_i\cdot\{g_jW_{11}^{2}W_{21}^{1}+g_pW_{21}^{2}W_{22}^{1}+g_sW_{31}^{2}W_{23}^{1}\} \\ 1 & 0\end{bmatrix},$$
$$B_{ijps}=\begin{bmatrix} g_i\cdot\{g_jW_{11}^{2}W_{31}^{1}+g_pW_{21}^{2}W_{32}^{1}+g_sW_{31}^{2}W_{33}^{1}\} \\ 0\end{bmatrix}, \tag{28}$$
$$X^T(k)=[x(k)\quad x(k-1)]$$

Step 2: The membership functions of two rules based fuzzy controllers can be

$$\text{IF}\quad x(k)\ \text{is}\ M_1(x(k))\ \text{and}\ M_2(x(k)) \\ \text{THEN}\quad u(t)=-F_1X(k)\ \text{and}\ -F_2X(k). \tag{29}$$

The overall fuzzy controller is $-M_1(x(k))F_1X(k)-M_2(x(k))F_2X(k)$ with $M_1(x(k))+M_2(x(k))=1$. The feedback gains F_1 and F_2 are determined by solving the inequalities (11) with a common positive definite matrix Q. Given $F_1=[2\quad -1]$, $F_2=[1\quad -2]$, the matrix Q could satisfy Lemma 3.1 so that $N(C;0)$ may not be asymptotically stable in the large in Fig. 6. The response of $N(C,0)$ cannot achieve the asymptotical stable. Therefore, $d(k)$ is added in front of $P(0;0)$.

Step 3: The nonlinear plant and its relaxed model are expressed in (30)-(31)

$$x(k+1)=-1.1\cdot x(k-1)+0.2\cdot(d(k)+x(k))^2\cdot u(k). \tag{30}$$

$$x(k+1)=-1.1\cdot x(k-1)+0.2\cdot\{\alpha_1(\beta_1+x(k))^2+\alpha_2(\beta_2+x(k))^2\}\cdot u(k) \tag{31}$$

with $\alpha_1=0.5$, $\alpha_2=1-\alpha_1=0.5$, and $\beta_1=-\beta_2=\xi$.

In order to stabilize $N_R(C;0)$, we substitute β_2 into (31) and result in

$$x(k+1)=-1.1\cdot x(k-1)+0.2\cdot x(k)^2\cdot u(k)+0.2\cdot\xi^2\cdot u(k) \tag{32}$$

Subsequently, we assume $\bar{u}(k)\equiv u(k)+e(k)$ and $u(k)$ is replaced by $\bar{u}(k)$ to be the input variable. After training, the NN relaxed model weights could be

$\overline{W}_{11}^{1}(\xi)=0.6121$, $\overline{W}_{12}^{1}(\xi)=0.7488$,
$\overline{W}_{13}^{1}(\xi)=-0.1561$, $\overline{W}_{21}^{1}(\xi)=-0.7145$,
$\overline{W}_{22}^{1}(\xi)=0.5766$, $\overline{W}_{23}^{1}(\xi)=-1.3012$,
$\overline{W}_{31}^{1}(\xi)=-0.3395$, $\overline{W}_{32}^{1}(\xi)=0.2211$,
$\overline{W}_{33}^{1}(\xi)=0.1189$, $\overline{W}_{11}^{2}(\xi)=-0.9481$,
$\overline{W}_{21}^{2}(\xi)=-1.0599$, $\overline{W}_{31}^{2}(\xi)=-0.3609$.

Eqs. (17)-(18), (26) are rewritten as

$$v_i^1=\overline{W}_{1i}^{1}(\xi)x(k)+\overline{W}_{2i}^{1}(\xi)x(k-1)+\overline{W}_{3i}^{1}(\xi)\bar{u}(k), \\ i=1,2,3 \tag{33}$$

$$v_1^2=\overline{W}_{11}^{2}(\xi)T_1^1(v_1^1)+\overline{W}_{21}^{2}(\xi)T_2^1(v_2^1) \\ +\overline{W}_{31}^{2}(\xi)T_3^1(v_3^1), \tag{34}$$

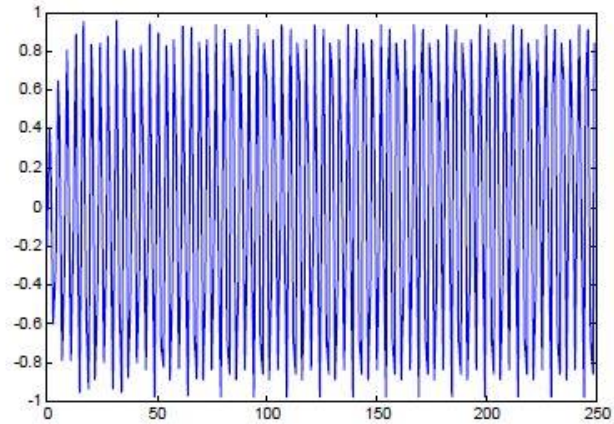


Fig. 6 The response of $x(k)$ for the closed-loop NN system $N(C;\ 0)$

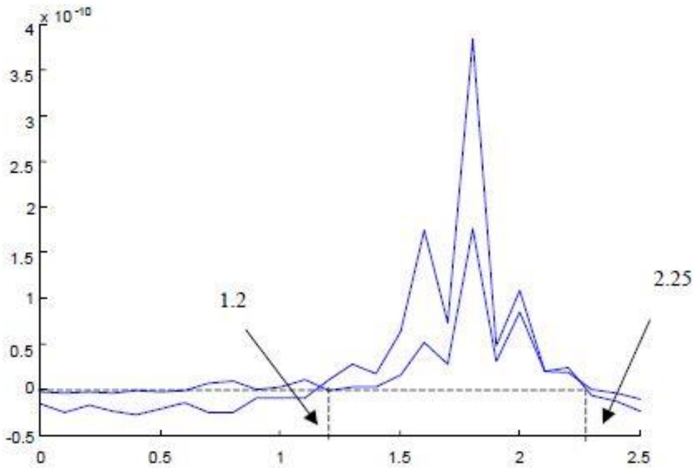


Fig. 7 The eigenvalues of the common matrix Q with respect to ξ

$$\begin{aligned} x(k+1) = \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2} & h_{1i}^{2}(k,\xi)h_{1j}^{1}(k,\xi)h_{2p}^{1}(k,\xi)h_{3s}^{1}(k,\xi) \times [g_i \cdot \{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{11}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{12}^{1}(\xi) \\ & + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{13}^{1}(\xi)\}x(k) + g_i \cdot \{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{21}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{22}^{1}(\xi) \\ & + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{23}^{1}(\xi)\}x(k-1) + g_i \cdot \{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{31}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{32}^{1}(\xi) \\ & + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{33}^{1}(\xi)\}\bar{u}(k)] \end{aligned} \tag{35}$$

$$\begin{aligned} = \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2} & h_{1i}^{2}(k,\xi)h_{1j}^{1}(k,\xi)h_{2p}^{1}(k,\xi)h_{3s}^{1}(k,\xi) \times [g_i \\ & \cdot \left\{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{11}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{12}^{1}(\xi) + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{13}^{1}(\xi)\right\}x(k) \\ & + g_i \cdot \left\{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{21}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{22}^{1}(\xi) + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{23}^{1}(\xi)\right\}x(k-1) \\ & + g_i \cdot \{g_j\overline{W}_{11}^{2}(\xi)\overline{W}_{31}^{1}(\xi) + g_p\overline{W}_{21}^{2}(\xi)\overline{W}_{32}^{1}(\xi) + g_s\overline{W}_{31}^{2}(\xi)\overline{W}_{33}^{1}(\xi)\}(1 - 0.2 \cdot \xi^2)u(k)]. \end{aligned} \tag{36}$$

The matrix representation is

$$x(k+1) = \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{p=1}^{2}\sum_{s=1}^{2} h_{1i}^{2}(k,\xi)h_{1j}^{1}(k,\xi)h_{2p}^{1}(k,\xi)h_{3s}^{1}(k,\xi) \times \left\{\overline{A}_{ijps}X(k) + \overline{B}_{ijps}u(k)\right\}, \tag{37}$$

where

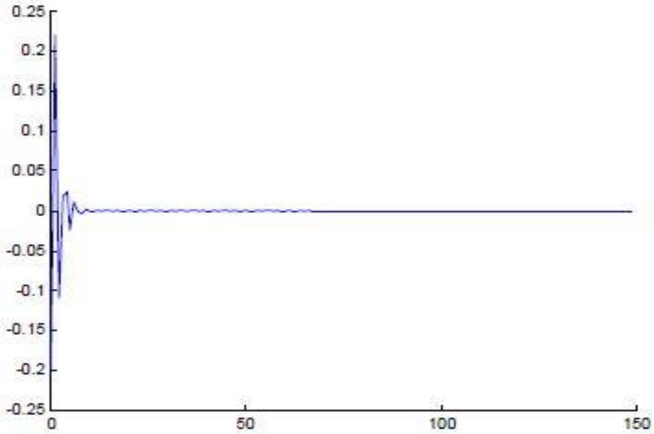
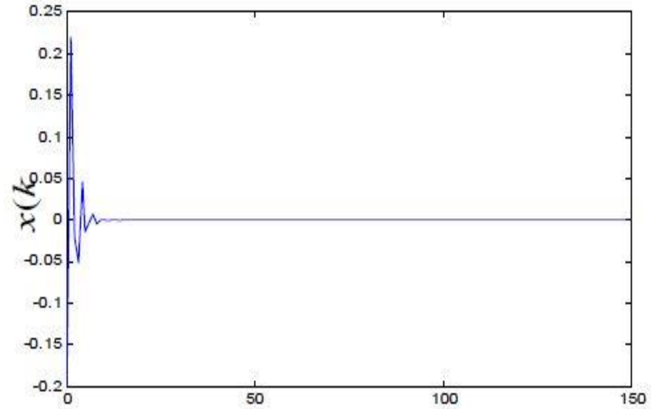
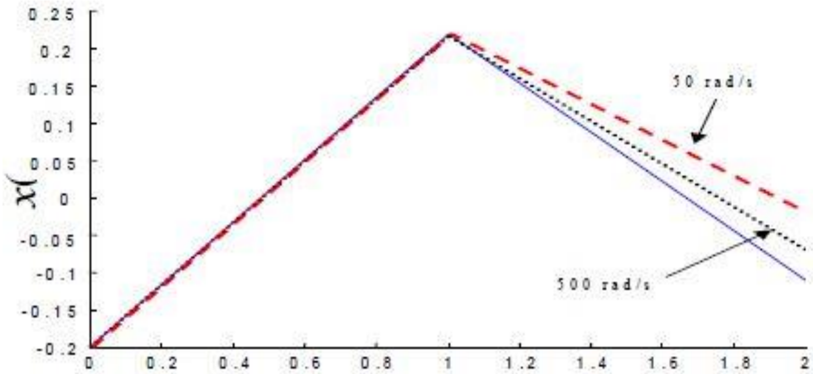


Fig. 8 The response of $x(k)$ for the closed-loop NN relaxed system $N_R(C;\ 0)$



(a)



(b)

Fig. 9 (a) The response of $x(k)$ for the closed-loop dithered system $P(C;\ d)$; (b) Simulation results of the closed-loop NN relaxed system $N_R(C;\ 0)$ and the closed-loop dithered system $X(C;\ d)$ ($\xi = 1.6, w = 50$ and w = 500 rad/s)

$$\overline{A_{ijps}} = \begin{bmatrix} g_i \cdot \begin{Bmatrix} g_j\overline{W}^2_{11}(\xi)\overline{W}^1_{11}(\xi) + g_p\overline{W}^2_{21}(\xi)\overline{W}^1_{12}(\xi) \\ +g_s\overline{W}^2_{31}(\xi)\overline{W}^1_{13}(\xi) \end{Bmatrix} & g_i \cdot \begin{Bmatrix} g_j\overline{W}^2_{11}(\xi)\overline{W}^1_{21}(\xi) + g_p\overline{W}^2_{21}(\xi)\overline{W}^1_{22}(\xi) \\ +g_s\overline{W}^2_{31}(\xi)\overline{W}^1_{23}(\xi) \end{Bmatrix} \\ 1 & 0 \end{bmatrix},$$

$$\overline{B_{ijps}} = \begin{bmatrix} g_i \cdot \{g_j\overline{W}^2_{11}(\xi)\overline{W}^1_{31}(\xi) + g_p\overline{W}^2_{21}(\xi)\overline{W}^1_{32}(\xi) + g_s\overline{W}^2_{31}(\xi)\overline{W}^1_{33}(\xi)\}(1 - 0.2 \cdot \xi^2) \\ 0 \end{bmatrix}.$$

With the interim (1.2 2.25), there exists a common positive definite matrix Q in Theorem 4.1 making $N_R(C;\ 0)$ is asymptotically stable shown in Fig. 7. Herein, ξ is chosen to be 1.6 in $N_R(C;\ 0)$ so that the response of $x(k)$ for $N_R(C;\ 0)$ is shown in Fig. 8 and the closed-loop $P(C;\ d)$ ($\omega = 50$ rad/s and $\omega = 500$ rad/s) is

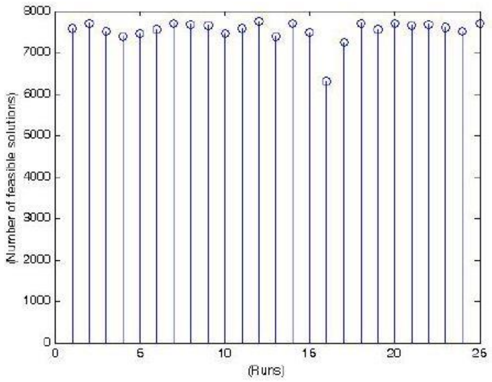


Fig. 10 Feasible solutions found by EBA in 25 runs

shown in Fig. 9. Obviously, the trajectory of is approximated by the trajectory of its corresponding relaxed system. That is, the controller can asymptotically stabilize the nonlinear system by appropriately regulating the amplitude. In the meanwhile, the number of feasible solutions obtained by EBA in different runs are shown in Fig. 10. The statistical analysis of the results obtained by EBA over 25 runs.

6. Conclusions

This paper displays a powerful way to deal with nonlinear frameworks. The NN is first settled to a nonlinear plant then the elements of the NN display is changed over into LDI portrayal. In this manner, a controller is intended to settle the nonlinear framework. On the off chance that the structured controller can't asymptotically balance out the NN demonstrate, a vacillate is infused and afterward the controller and the vacillate frequency circuit are all the while acquainted with asymptotically settle the shut circle framework. Reenactment results demonstrate that the controller with auxiliary circuit can asymptotically settle the shut circle framework by fittingly directing the plentifulness of vacillate when the vacillate's recurrence is sufficiently high. The merits of the EBA model also provide the flexibility and feasibility by searching the solutions of the controlled systems.

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