JIAS
Journal of Intelligent Automation Systems
Published online: 05 February 2014

Modification of Feedback Error Learning Technique for Desired Trajectory Tracking in the Presence of Disturbance

Hossein Gholizade_Narm [a,*]

Abstract: An improved version of feedback error learning (FEL) method is proposed for tracking desired trajectory in the presence of disturbance. As the feedback error learning technique is closely related to Nonlinear Adaptive Control (NLAC), the modification of NLAC for disturbance rejection is also focused on this paper. The sufficient conditions are obtained for asymptotically stability with lyapunov method and adaptation laws are presented for estimation of unknown parameters . It mathematically indicates that the use of FEL method normally cannot eliminate disturbance. Also, non-linear adaptive control method has not the ability to accurately estimate the unknown parameters and cannot provide zero tracking error in the presence of disturbance. Moreover, adding an integrator to both methods normally cannot resolve the problem. . In this paper, a modification is proposed to solve the problem. The simulation results confirm the ability of proposed modification for disturbance rejection.

Keywords: Feedback Error Learning, Nonlinear Adaptive Control, Tracking, Disturbance Rejection, Parameter Estimation

**Corresponding author. a Electrical and Robotic Department, Shahrood Unversity of Technology; e-mail: gholizade@shahroodut.ac.ir, h_gholizade@yahoo.com*

1. Introduction

Feedback error learning (FEL) method has recent been the focus on some studies [1,2]. It was introduced by Kawato and his colleagues (1987) as a motor control of cerebellum model [3]. The controller is composed of two sub-controllers. The first controller is adaptive and updated using feedback error. The second one is a typical classic controller and causes stability in error dynamical system. Figure (1) illustrates the schematic of controller.

In this schematic diagram, the feed-forward controller acts as an adaptive controller and provides the inverse model. The feedback controller forces error to zero. The main disadvantage of this approach is the need to reverse the under-control system. To resolve this problem, Kawato and colleagues presented a different approach in 1990, and used adaptive feedback instead of a feed-forward controller [4]. In this method, the system would be linearized if it was nonlinear using a feedback linearization technique. Figure (2) shows the block diagram of FEL with the state feedback adaptive controller.

If the system has unknown parameters, by using the adaptive method, in conjunction with feedback control, the parameter estimation procedure is performed in the two methods above. The persistency of excitation should be highly enough for the accurate parameter estimation. In [5], the FEL is discussed for multi-variable system with insufficient persistency. The presented method receives help from frequent responses for the parameter estimation.

FEL method and adaptive control are closely related [6]. In the point of view of control theory, the FEL method can be created by adaptive control techniques [7,8]. FEL stability analysis for a class of linear systems of the robot arm was designed by Miyamura [8]. Miyamura was limited to linear stable and reversible stable systems in the under-study system.

The delay in providing feedback is a major problem in control of dynamical systems. Miyamura and Kimura studied the effect of delay on FEL performance and system stability [9,10]. In 2004, Nakanishi et. al. [6] studied the FEL from viewpoint of the nonlinear adaptive control techniques. They showed that the two methods differ only in adaptation law. Their approach was a major flaw and it was inability to reject the input disturbance. The system proposed by Nakanishi is driven by disturbance, and neither the tracking error nor unknown parameters of the system are not well estimated. In this paper, the effect of constant disturbance on system performance and changing the adaptation rules and error gain vector were examined to reject disturbance completely.

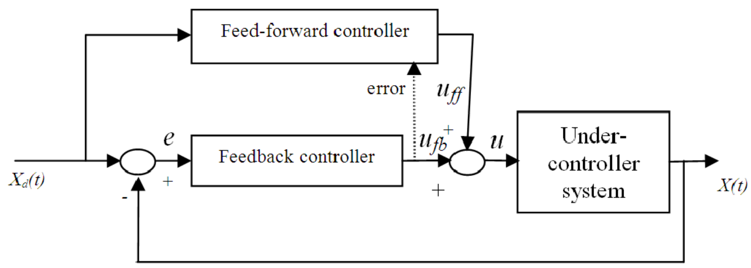


Fig. 1: Schematic diagram of FEL

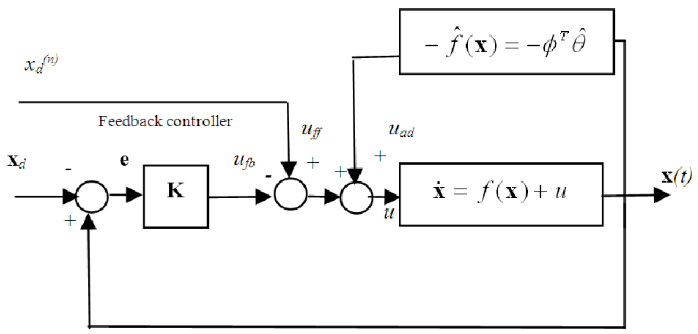


Fig. 2: FEL method with the state feedback adaptive controller for nonlinear SISO system order n

The paper is organized as follow: First, the problem is clearly stated. Second, the FEL and NLAC are introduced in the presence of disturbance. Third, the stability of FEL and NLAC is presented for a system of second order . Fourth, the modified FEL and NLAC are proposed to reject the disturbance and accurate convergence of unknown parameters. Fifth, the performance of proposed method is illustrated on stable /unstable, linear/nonlinear plants. In last section, conclusions are provided.

2. problem statement

Due to the advantages of feedback on the feedforward technique, the configuration of Figure (2) is used. As stated in this model, it is not necessary to reverse the under control system. For simplicity, a single input - single output (SISO) is considered.

$$\begin{aligned} \dot{x}_1 &= x_2 \\ &\vdots \\ \dot{x}_{n-1} &= x_n \\ \dot{x}_n &= f(\mathbf{x}) + u \end{aligned} \tag{1}$$

where $\mathbf{x} = [x_1, x_2, ..., x_n] \in R^n$, x=x_1 and u $\in R$

Suppose $f(X)$ is linearly parameterized as follows:

$$f(\mathbf{x}) = \varphi^T(\mathbf{x})\theta + \Delta(\mathbf{x}) \tag{2}$$

where φ is the nonlinear basis functions and is equal to $\varphi = \begin{bmatrix}\varphi_1^T & \varphi_2^T & ... & \varphi_N^T\end{bmatrix}^T$ and θ is the parameters vector as $\theta = \begin{bmatrix}\theta_1^T & \theta_2^T & ... & \theta_N^T\end{bmatrix}^T$. $\Delta(\mathbf{x})$ is also the approximation error. since the structure of f(x) is assumed known, then $\Delta(\mathbf{x})$ is zero.

3. FEL and NLAC against constant disturbance

One issue that most real systems are involved is disturbance in their input. There are several approaches to deal with the disturbance. A common method for disturbance rejection is such as adding an error integrator in control law. In this case, since the open-loop system has an integrator, the closed loop system is stable, and it will have the ability of disturbance rejection. After that, we will see the addition Integrator without changing and updating the adaptation rules, and the unknown parameters will not converge to the correct parameters, and fluctuated tracking error does not tend to zero either.

In this paper, a technique is proposed that the unknown parameters converge to the correct parameters and also tracking error approaches to zero with minimal oscillation.

3.1. Adaptive feedback

According to Figure (2), the control law is obtained as follows:

$$u = u_{ad} + u_{ff} - u_{fb} := -\hat{f}(\mathbf{x}) + x_d^{(n)} - \mathbf{Ke} \tag{3}$$

where $u_{ad} = -\hat{f}(\mathbf{x})$, $u_{ff} = x_d^{(n)}$ and $u_{fb} = \mathbf{Ke}$. In this law, $\hat{f}(\mathbf{x})$ and $x_d^{(n)}$ are used for linearization and tracking respectively. ($x_d^{(n)}$ is the n^{th} order derivative of the desired trajectory)

Feedback row vector and error column vector using this method are as follows, respectively.

$$\mathbf{k} = [k_1, k_2, \ldots, k_{n+1}] \tag{4}$$

$$\begin{aligned} \mathbf{e} &= [\int edt \; e \; \dot{e} \; . . . \; e^{(n)}]^T \\ e &= x - x_d \end{aligned} \tag{5}$$

It is noted that In equation (5), the Integral of error is logged in the error vector. This is due to eliminate disturbance. It will be seen that the disturbance cannot be rejected just by adding an integrator term and the tracking error will not tend to zero. By substituting the control law in the equation (1), the error dynamic equations are obtained.

$$\hat{f}(\mathbf{x}) = \varphi^T(\mathbf{x})\hat{\theta} \tag{6}$$

$$\dot{\mathbf{e}} = A\mathbf{e} + b(f - \hat{f}) = A\mathbf{e} + b(-\varphi^T\tilde{\theta})$$

$$A = \begin{bmatrix} 0 & 1 & ... & 0 \\ 0 & 0 & ... & 0 \\ \vdots & & & \\ 0 & 0 & ... & 1 \\ -k_1 & -k_2 & ... & -k_{n+1} \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ 0 \\ . \\ . \\ 1 \end{bmatrix} \tag{7}$$

where $\hat{\theta}$ is the estimated value of θ parameters. The feedback gain vector is chosen such that the matrix A is stable.

3.2. Stability analysis and adaptation rule extraction

Consider the Lyapunov function as follow.

$$V = \frac{1}{2}\mathbf{e}^T S\mathbf{e} + \frac{1}{2}\tilde{\theta}^T \Gamma^{-1}\tilde{\theta} \quad (8)$$

where S and Γ are positive definite matrices. Since matrix A is stable, there are two positive definite matrices S and L such that [12,13]:

$$A^T S + SA = -L \\ Sb = \mathbf{c}^T \quad (9)$$

Define,

$$e_1 \overset{\Delta}{=} \mathbf{ce} \quad (10)$$

The time derivative of the Lyapunov function is:

$$\begin{aligned} \dot{V} &= \frac{1}{2}(\dot{\mathbf{e}}^T S\mathbf{e} + \mathbf{e}^T S\dot{\mathbf{e}}) + \tilde{\theta}^T \Gamma^{-1}\dot{\tilde{\theta}} \\ &= \frac{1}{2}\mathbf{e}^T (A^T S + SA)\mathbf{e} + \tilde{\theta}^T \Gamma^{-1}(\dot{\tilde{\theta}} - \Gamma\varphi e_1) \\ &= -\frac{1}{2}\mathbf{e}^T L\mathbf{e} + \tilde{\theta}^T \Gamma^{-1}(\dot{\tilde{\theta}} - \Gamma\varphi e_1) \end{aligned} \quad (11)$$

The adaptation rule is defined as follow,

$$\dot{\tilde{\theta}} = \dot{\hat{\theta}} = \Gamma\varphi(\mathbf{x})e_1 \quad (12)$$

Therefore, the Lyapunov time derivative is:

$$\dot{V} = -\frac{1}{2}\mathbf{e}^T L\mathbf{e} \le 0 \quad (13)$$

Hence the error dynamic equation is stable because: $V(t) \le V(0)$ therefore e and $\tilde{\theta}$ are bounded. Since $\ddot{V}$ is also bounded so $\dot{V}$ is uniformly continuous and according to Barbalat lemma, the error vector tends to zero [11].

The vector c is, c=[$k_1,\ldots,k_{n+1}$] and $\mathbf{c} = [\Lambda_1 \;\; \Lambda_2 \;\; \ldots \;\; \Lambda_{n+1}]$ for FEL and NLAC, respectively and should be chosen such that (a,b,c) be positive real [6]. It is clear that the degree of freedom to choose the NLAC parameters is greater than one of FEL. Afterwards, how to choose a vector "**c**" for a second order System is explained.

4. FEL and NLAC Stability conditions

Achieving to stability conditions that involves finding necessary relationships in which A, b, c are positive real is difficult in general. Here, we study the sufficient conditions for the stability of a typical second order system.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -k_I & -k_P & -k_D \end{bmatrix} \quad (14)$$

Sufficient conditions for the stability of FEL technique is where $\mathbf{c} = [k_I \;\; k_P \;\; k_D]$,

1- All eigenvalues of the matrix A have a negative real value. Therefore, the following condition is satisfied:

$$k_I < k_P k_D \quad (15)$$

2- CB=(CB)T>0

This condition is established for the system order 2 because:

$cb=(cb)^T=k_D>0$

3- The (A, B, C) must be positive real [8]:

$CAB+(CAB)^T < 0$

The following conditions must be established for the system of second order:

$$2(k_P - k_D^2) < 0 \Rightarrow k_P < k_D^2 \quad (16)$$

Aforementioned conditions are for FEL. NLAC should be established for the following conditions. The vector c is $\mathbf{c} = [\Lambda_1 \;\; \Lambda_2 \;\; \Lambda_3]$ in this case.

1- all eigenvalues of the matrix A have negative real value.

$$k_I < k_P k_D \quad (17)$$

2- CB=(CB)T>0

This condition is established for the second order system because:

$cb=(cb)^T=\Lambda_3>0$

3- The (A, B, C) must be positive real

$$CAB+(CAB)^T < 0 \\ \Rightarrow 2(\Lambda_2 - \Lambda_3 k_D) < 0 \\ \Rightarrow \Lambda_2 < \Lambda_3 k_D \quad (18)$$

Given these relationships, it can be seen that the choice of the feedback gain in FEL is more limited than NLAC.

5. Modification of FEL and NLAC for disturbance rejection

Assume a constant disturbance d enters into the second order system.

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \varphi^T(\mathbf{x})\theta + u + d \\ u &= -\varphi^T(\mathbf{x})\hat{\theta} + \ddot{x}_d - k_I\int e\,dt - k_P e - k_D\dot{e} \\ e &= x - x_d \end{aligned} \quad (19)$$

By substituting the control law in the system dynamic equations:

$$\begin{aligned}\ddot{x} &= \varphi^T(\mathbf{x})\theta - \varphi^T(\mathbf{x})\hat{\theta} + \ddot{x}_d - k_I\int edt - k_P e - k_D\dot{e} + d \\ &= \varphi^T(\mathbf{x})(\theta - \hat{\theta}) + \ddot{x}_d - k_I\int edt - k_P e - k_D\dot{e} + d \\ \ddot{e} &= \ddot{x} - \ddot{x}_d = -k_I\int edt - k_P e - k_D\dot{e} + d + \varphi^T(\mathbf{x})\tilde{\theta} \\ \tilde{\theta} &= \theta - \hat{\theta}\end{aligned} \tag{20}$$

Suppose $\hat{\theta}$ is very close to θ, then we have:

$$\ddot{e} \cong -k_I\int edt - k_P e - k_D\dot{e} + d \tag{21}$$

$$\dddot{e} \cong -k_I e - k_P\dot{e} - k_D\ddot{e} \tag{22}$$

Given the choice of coefficients $\mathbf{c} = [k_I \ k_P \ k_D]$, error dynamic equation is stable, So the error and its first and second derivatives in the absence and presence of constant disturbances tend to zero.

$$e \to 0, \dot{e} \to 0, \ddot{e} \to 0 \tag{23}$$

If d = 0, the vector error $\mathbf{e} = [\int edt \ e \ \dot{e}]$ will tend to zero. However, if d is fixed and nonzero, according to equation (21), we have:

$$k_I\int edt \to d, \dot{e} \to 0, e \to 0 \tag{24}$$

Again the tracking error (e) is zero, but we should be sure that all these things are true when $\theta \to \hat{\theta}$.

With the implementation of the adaptation rule, it is observed that the above assumption is not acceptable.

$$\begin{aligned}\dot{\hat{\theta}} &= \Gamma\varphi(\mathbf{x})e_1 \\ e_1 &= \mathbf{ce}\end{aligned} \tag{25}$$

5.1. Adaptation rule for FEL

$$\begin{aligned}&\mathbf{c} = [k_I \ k_P \ k_D], \\ &e_1 = k_I\int edt + k_P e + k_D\dot{e}\end{aligned} \tag{26}$$

5.2. Adaptation rule for NLAC

$$\begin{aligned}&\mathbf{c} = [\Lambda_1 \ \Lambda_2 \ \Lambda_3] \\ &e_1 = \Lambda_1\int edt + \Lambda_2 e + \Lambda_3\dot{e}\end{aligned} \tag{27}$$

If the disturbance does not enter into the system, the error vector tends to zero, then $e \to 0$, which yields:

$$\dot{\hat{\theta}} = \Gamma\varphi(x)e_1 \to 0 \tag{28}$$

Equation (28) states that the fluctuation of $\hat{\theta}$ goes to zero and the $\hat{\theta}$ become fixed. If the persistency of excitation is high enough, the $\hat{\theta}$ will tend to θ [12]. Now, if *d=cte.* ≠ 0, it was shown in equation (21) that $\int edt = d/k_I$ and never be zero. therefore $e_1 \to d$ and $\dot{\hat{\theta}}$ does not tend to zero. This means that the recent assumption is not correct. Consequently the FEL technique in usual form doesn't act properly and should be modified. This is also true for NLAC. Because $e_1 \to \Lambda_1\int edt = d$. Regarding the adaptation rule, it can be seen that the integrator is causing the problem. On the other hand, If there is no Integrator, the error does not tend to zero in the presence of disturbance. Therefore, to solve this problem, we set the first term in vector c equal to zero. Be careful that this selection does not mean of putting $k_I = 0$ in the feedback vector.

In the case of FEL:

$$\mathbf{c} = [0 \ k_P \ k_D] \tag{29}$$

And In the case of NLAC:

$$\mathbf{c} = [0 \ \Lambda_2 \ \Lambda_3] \tag{30}$$

It is clear that the selection vector c as above doesn't violate the stability conditions (15-18). With this choice for the FEL, we have:

$$e_1 = k_P e + k_D\dot{e} \tag{31}$$

And for NLAC:

$$e_1 = \Lambda_2 e + \Lambda_3\dot{e} \tag{32}$$

In this case, since $\dot{e} \to 0$, $e \to 0$ consequently $e_1 \to 0$ and $\dot{\hat{\theta}} \to 0$. It means that $\hat{\theta}$ tends to a fixed value. Now, if the persistency excitation of the input signal is 2 then $\hat{\theta} \to \theta$. According to (20), we have:

$$\ddot{x} - \ddot{x}_d \to 0 \ \Rightarrow \ddot{x} \to \ddot{x}_d \ \Rightarrow x \to x_d \tag{33}$$

It means tracking is fully done and the disturbance is removed. In equation (19), we saw that the disturbance is completely eliminated by u because $k_I\int edt \to d$. Accordingly

$$u \to -\varphi(\mathbf{x})\theta + \ddot{x}_d - d \tag{34}$$

In other words, the mirror of disturbance is created in control signal and eliminates it completely.

5.3. Speed up of convergence

In the adaptation rule only an integrator was used. To speed up the convergence of unknown parameters, a proportional term is also added [12]. The resulted adaptation rule is as follow:

$$\hat{\theta} = \Gamma_1 \varphi(x) e_1 + \int (\Gamma_2 \varphi(x) e_1) dt \tag{35}$$

6. Simulation

In this section, a second prototype system in both stable and unstable mode is simulations to track the desired trajectory. The controller is designed based on two methods (FEL and NLAC) and described in the previous section. Moreover, a nonlinear system is simulated too.

Consider the following system of second order:

$\ddot{x} = -m\dot{x} - nx + u$

Where u is input signal and m and n are system's coefficients. This system can be stable and unstable considered to m and n .

a- Stable case: m = 2, n = 1

b- Unstable case: m = -2, n = -1

Control signal is:

$u = -\hat{m}\dot{x} - \hat{n}x + \ddot{x}_d - (k_I \int edt + k_P e + k_D \dot{e})$

Consider the desired trajectory as follows:

$x_d(t) = \sin 2\pi t$

The persistency excitation of desired trajectory is 2. Therefore, two parameters can be estimated without error. The tracking error is defined as:

$e = x - x_d$

Consider the adaptation parameters as:

$\Gamma_1 = 0.05 I_{2x2}$, $\Gamma_2 = 0.8 I_{2x2}$

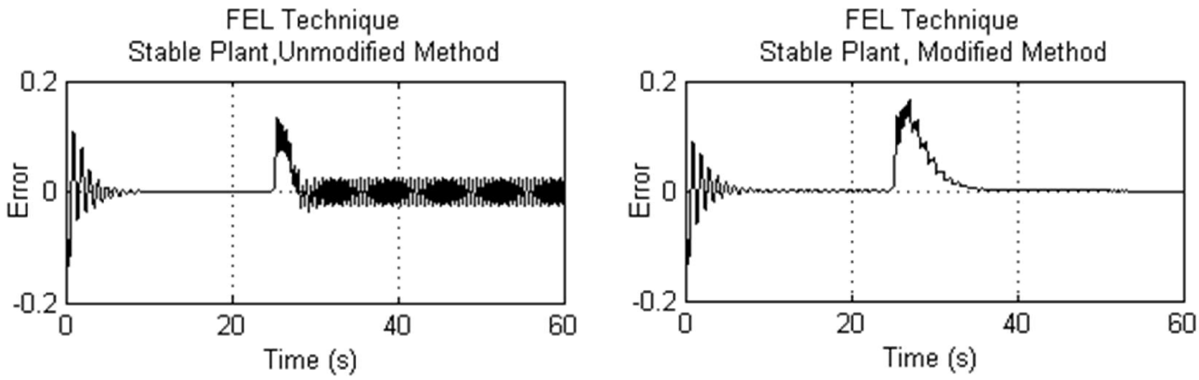
$[\Lambda_1 \ \Lambda_2 \ \Lambda_3] = [1 \quad 1 \quad 5]$

$[k_I \ k_P \ k_D] = [5 \quad 5 \quad 3]$

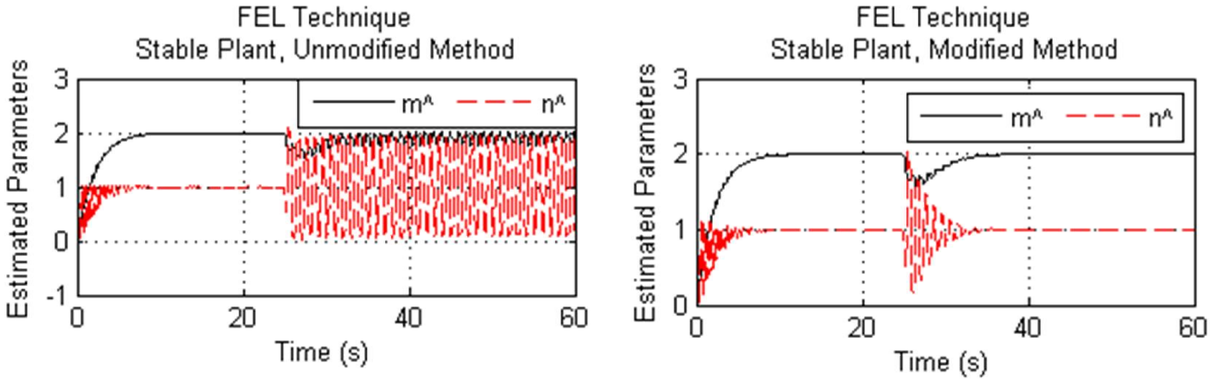
It is clear that with selected K and Λ vectors, the stability conditions have been met. Figure (3) illustrates the performances of unmodified and modified FEL controllers on the stable system.

Figure (3) shows that before entering the disturbance, with both unmodified and modified FEL controller, the tracking well done and parameters converge to the correct value but after entering disturbance at the moment 25 (t=25 sec.), tracking error oscillates and does not tend to zero for unmodified FEL. Also the estimated parameters fluctuate greatly after disturbance. The performance of modified FEL shows that it is robust against disturbance and the tracking error tends to zero in the presence of disturbance. The parameters also can be estimated accurately.

Figure (4) illustrates the performances of unmodified and modified FEL controllers on the unstable system.

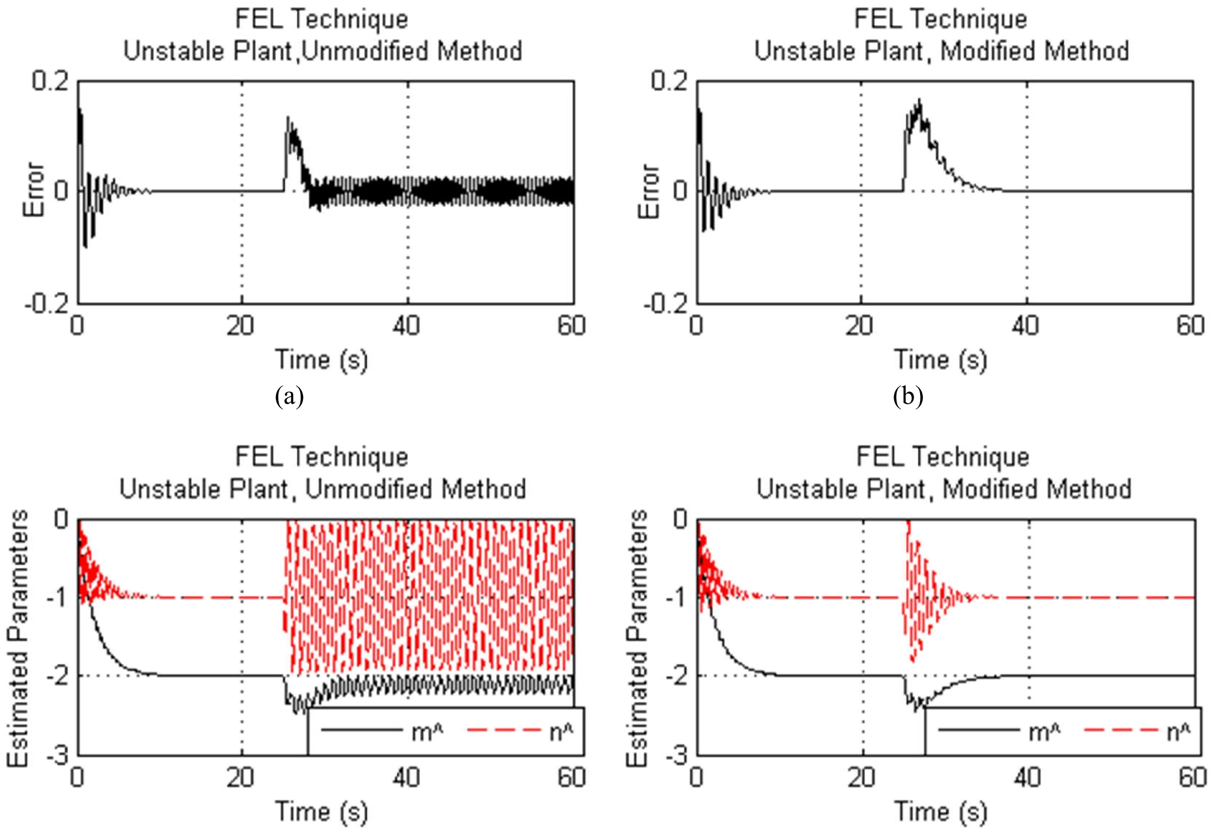


(a) (b)



(c) (d)

Fig. 3: The performances of unmodified and modified FEL controllers on the stable system. The disturbance is entered on t = 25 sec. a) tracking error for unmodified FEL, b) tracking error for modified FEL, c) parameter estimation for unmodified FEL, d) parameter estimation for modified FEL



(c) (d)

Fig. 4: The performances of unmodified and modified FEL controllers on the unstable system. The disturbance is entered on t = 25 sec. a) tracking error for unmodified FEL, b) tracking error for modified FEL, c) parameter estimation for unmodified FEL, d) parameter estimation for modified FEL

Figures 3 and 4 show that the stability of under-control system does not have effect on the performance of modified FEL. This is another advantage of modified FEL technique.

Figure (5) illustrates the performances of unmodified and modified NLAC on the stable system.

The NLAC acts like FEL. It is not able to reject disturbance in unmodified mode and can remove the disturbance completely in modified model.

Figure (6) illustrates the performances of unmodified and modified NLAC on the unstable system.

As expected, for both stable and unstable modes, the performance of the controller does not differ.

To show the ability of proposed method, a nonlinear second order system is also simulated. The nonlinear system is $\ddot{x} = -m\dot{x} - n(x - x\sin(\dot{x})) + u$. The parameters are considered as before for FEL and NLAC. Simulation results are illustrated in Figure (7).

The comparison Figure (7) with previous Figures reveal that the proposed method is free of the linearity of systems. The only condition is that the systems should be linear in unknown parameters.

7. Conclusion

In this paper, first a summary of the technique of feedback error learning and nonlinear adaptive control were expressed and in the control law, adaptation rules and closed-loop system stability were discussed. It was considered that without modification in FEL and NLAC techniques, the closed loop system has not good performance in the presence of disturbance and in addition to steady state error, the unknown parameters were not converged to the correct values. To solve this problem, at first, an integrator was added to control law and its effects on the error dynamics and stability of the closed loop system was analyzed. According to new control law, the adaptation rules are achieved through using lyapunov stability analysis. Moreover, sufficient conditions for the stability of the closed loop system of second order was presented. The finding of this study

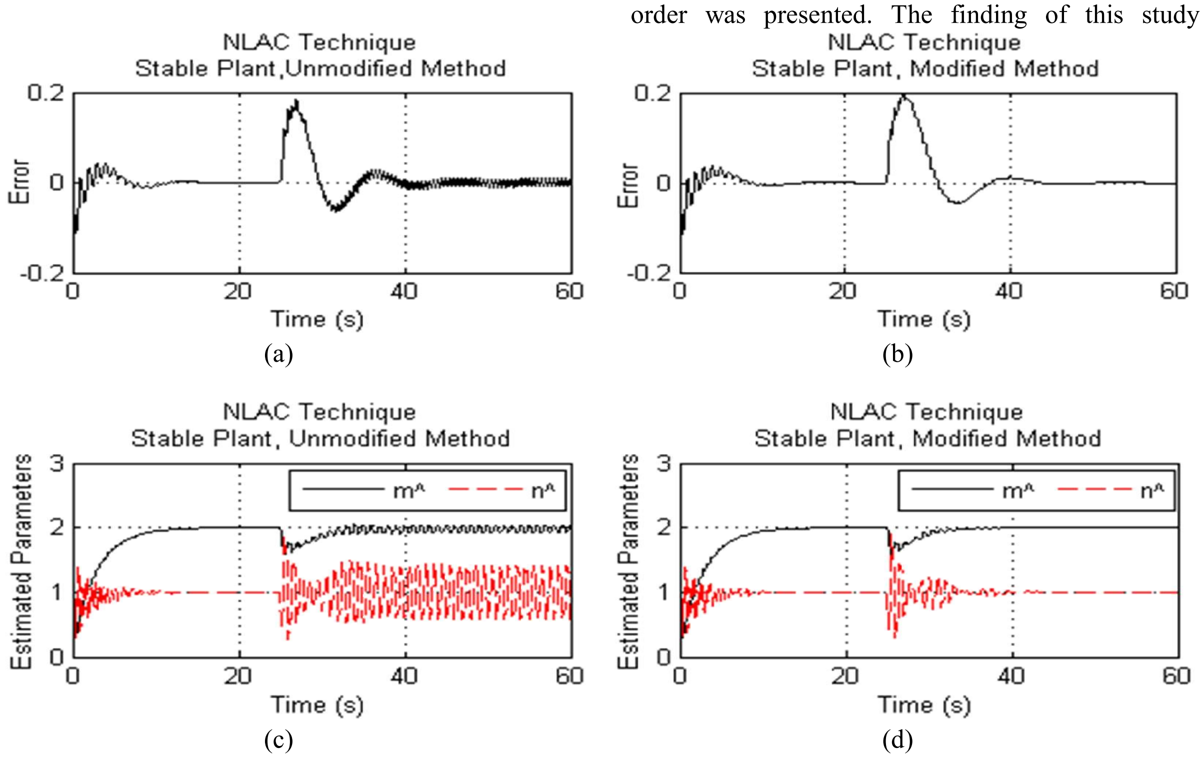


Fig. 5: The performances of unmodified and modified NLAC on the stable system. The disturbance is entered on t = 25 sec. a) tracking error for unmodified NLAC, b) tracking error for modified NLAC, c) parameter estimation for unmodified NLAC, d) parameter estimation for modified NLAC

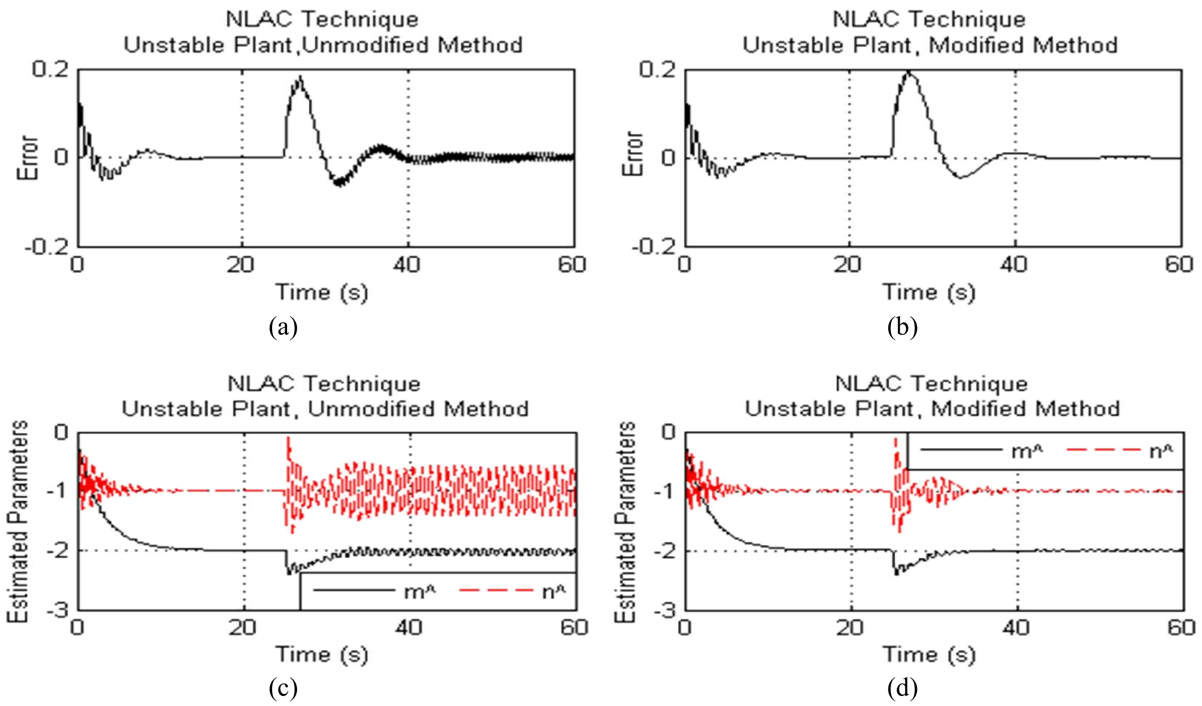


Fig. 6: The performances of unmodified and modified NLAC on the unstable system. The disturbance is entered on t = 25 sec. a) tracking error for unmodified NLAC, b) tracking error for modified NLAC, c) parameter estimation for unmodified NLAC, d) parameter estimation for modified NLAC

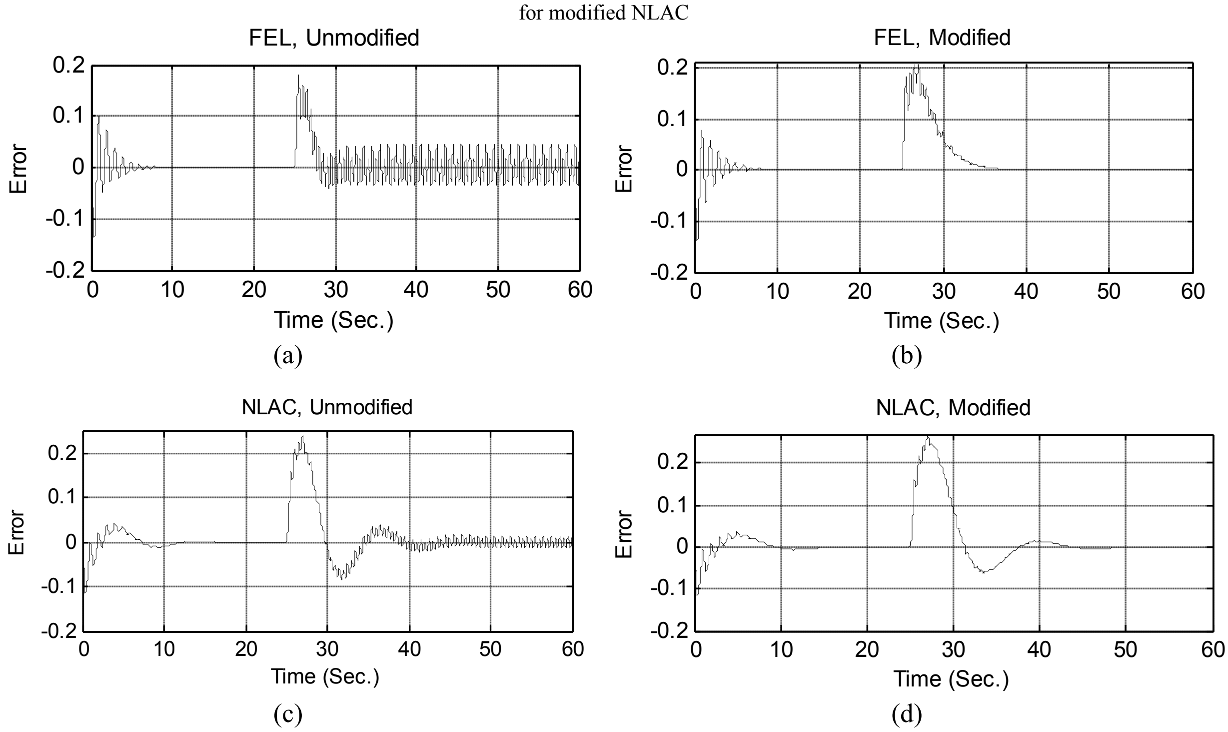


Fig. 7: The performances of unmodified and modified FEL and NLAC on the nonlinear system. The disturbance is entered on t = 25 sec. the subplots are tracking error for a) Unmodified FEL, b) Modified FEL c) Unmodified NLAC, d) Modified NLAC

indicates when the steady state error is zero, complete tracking is performed. It was confirmed that the unknown parameters converge to the correct values for proposed modification. Simulation results also showed the robustness of the proposed FEL and NLAC. The NLAC in comparison with FEL has more degree of freedom and therefore, it acts better regarding to tracking and estimation.

References

[1] Silvia Tolu, Mauricio Vanegas,Niceto R. Luque,Jesús A. Garrido,Eduardo Ros, Bio-inspired adaptive feedback error learning architecture for motor control, Biological Cybernetics, **106**(8-9), 507–522, (2012).

[2] T. Watanabe, K. Fukushima., A study on feedback error learning controller for functional electrical stimulation: generation of target trajectories by minimum jerk model, Artif Organs. **35**(3), 270–4, (2011).

[3] M. Kawato, A hierarchical neural-network model for control and learning of voluntary movement, Biological Cybernetics, **57**, 169–185, (1987).

[4] M. Kawato, Feedback-error-learning neural network for supervised motor learning, Advanced neural computers, Amsterdam: Elsevier, 365–372, (1990).

[5] K. Sugimoto, B. Alali, and K. Hirata, Feedback Error learning with insufficient excitation, 47th IEEE Conference on Decision and Control, Cancun, Mexico, Dec. 9-11, 2008.

[6] J. Nakanishi, S. Stefan, Feedback error learning and nonlinear adaptive control, Neural Network **17**, 1453–1465, (2004).

[7] K. Doya, K. Kimura, A. Miyamura, Motor control: Neural model and system theory, International Journal of Applied Mathematics and Computer Science, **11**(1), 77–104, (2001).

[8] A. Miyamura and H. Kimura, Stability of feedback error learning scheme, System and Control Letters, **45**(4), 303–316, (2002).

[9] A. Miyamura and H. Kimura, Stability of feedback error learning method for general plants with time delay, 15th Triennial World Congress, Barcelona, Spain, 2002 IFAC.

[10] A. Miyamura, Stability of feedback error learning method with time delay, Neurocomputing, **69**(13-15), (2006).

[11] K. Hassan Khalil, Nonlinear Systems, Third Edition Prentice Hall, 2002, ISBN 0-13-067389-7.

[12] K.J. Åström, B. Wittenmark, Adaptive Control, Addison-Wesley, 1995.

[13] C.T. Chi-Tsong Chen, Linear system theory and design, Oxford University Press, 1999.