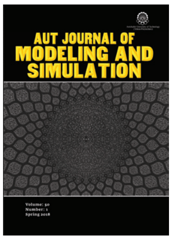

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Robust Adaptive Control of Voltage Saturated Flexible Joint Robots with Experimental Evaluations

A. Izadbakhsh*

Department of Electrical Engineering, Garmsar Branch, Islamic Azad University, Garmsar, Iran

ABSTRACT: This paper is concerned with the problem of designing and implementing a robust adaptive control strategy for the flexible joint electrically driven robots (FJEDR) while considering the constraints on the actuator voltage input. The control design procedure is based on the function approximation technique, to avoid saturation besides being robust against both structured and unstructured uncertainties associated with external disturbances and un-modeled dynamics. Stability proof of the overall closed-loop system is given via the Lyapunov direct method. The analytical studies as well as experimental results obtained using MATLAB/SIMULINK external mode control on a single-link flexible joint electrically driven robot, demonstrate a high performance of the proposed control schemes.

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1- Introduction

The actuator input constraints are one of the major problems that arise while controlling an actuated dynamic system. These constraints are due to either physical limitations of the devices or practical reasons that restrict the command signal coming from the controller to the actuators [1-2]. When an actuator has reached such an input limit, further efforts to increase the actuator input would not result in any variation in the output [3]. To deal with these problems, many valuable torque-based control strategies have been proposed by researchers, aiming to prevent instability and nominal performance degradations of the robotic systems considering input constraints [4-9]. The considerable point is that although these approaches are satisfactory in principle, they are often criticized for few reasons, as mentioned in [10].

To tackle these problems, some related works in the field of adaptive/robust control have been proposed [11-16]. Moreover, several approaches to minimize the performance loss due to input constraints have been reported [17]. However, there are yet other problems. The conventional adaptive control scheme requires the computation of the regressor matrix, persistent excitation (PE) being condition of the reference input signal due to the convergence of the parameter's vector, and slow behavior of the dynamic system. This problem becomes hypersensitive especially for higher degree of freedom (DOF) robot manipulators. Furthermore, they are unable to handle unstructured uncertainty and external disturbances adequately, which is a missing link in almost all the addressed approaches [18].

To cope with these problems, a robust adaptive control has been proposed. Robust adaptive control enhances the robustness of adaptive control. The need for robust adaptive control is based on the observation that robotic manipulators may have unparameterizable dynamics such as friction, external disturbances, and unmodeled dynamics. Any of these dynamics can potentially destabilize the system since the time derivative of the Lyapunov function is only negative semi-definite under adaptive control. There are two ways to generate robustified adaptive controls, called robust adaptive control, namely,

I) the first method is to add min-max control to the existing adaptive control. The robust control part compensates for those unparameterizable dynamics, and therefore only requires their bounding function [19].

II) The second method of designing robust adaptive control is to change the adaption law by using the so-called leakage-like adaption law [20]. Compared with the standard adaptive control law, the leakage-like adaptive control law achieves robust stability in the presence of disturbances and uncertainty with compromising tracking precision.

Recently, regressor-free control of robot manipulators has been proposed which is based on function approximation techniques (FAT) [21-23]. [22] shows that uncertainties can be approximated by a simple p- order linear differential equation. Thus, it can be handled by means of a simple well-known model reference adaptive control technique which facilitates the analysis and the design task as well. [23] presented a back-stepping like controller design based on slotine-Lee scheme. However, the number of DOF and the weighting matrices dimension are the important issues that impose an extra computational load, which in turn affect the controller performance [24].

The contribution of this article lies in the design of a FAT-Based robust adaptive control scheme for FJEDR, in which parameter uncertainties and even actuator saturation nonlinearity are considered. The control design strategy is based on a third order instead of fifth order dynamic model. Compared to other previous FAT-based adaptive control strategies proposed for FJEDR, the proposed approach has a less computational load that is suitable for practical

Corresponding author; Email: izadbakhsh_alireza@hotmail.com

implementation. It also considers the external disturbances effects, which is the main concern in conventional Model Reference Adaptive Control (MRAC) [1].

This paper is organized as follows. Section 2 briefly presents the modeling of the FJEDR. Section 3 is devoted to the description of the proposed control scheme. Stability analysis and performance evaluation are presented in section 4. The experimental setup and real time results are described and presented in section 5. Finally, concluding remarks are drawn in section 6.

2- Modeling with Considering Saturation

The dynamics in joint space of a serial-chain n-link FJEDR considering actuator voltage input constraint can be written as [2]

$$D(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}+g(\theta)=K(r\theta_m-\theta) \tag{1}$$

$$J\ddot{\theta}_m+B\dot{\theta}_m+rK(r\theta_m-\theta)=K_m I_a \tag{2}$$

$$L_a\dot{I}_a+R_a I_a+K_b\dot{\theta}_m+\varphi(t)=sat(u(t)) \tag{3}$$

where $\theta,\dot{\theta},\ddot{\theta}\in\Re^n$ are link position, velocity, and acceleration, respectively. $D(\theta)\in\Re^{n\times n}$ is a symmetric, positive-definite function called inertia matrix, $C(\theta,\dot{\theta})\in\Re^{n\times n}$ is a matrix function called centrifugal and Coriolis forces matrix, and $g(\theta)\in\Re^n$ is gravity terms. $\theta_m,\dot{\theta}_m,\ddot{\theta}_m\in\Re^n$ are the joint position, velocity, and acceleration, respectively; the constant, positive diagonal matrices K, J, B, K_m, L_a, R_a, and $K_b\in\Re^{n\times n}$ represent flexibility, inertia, damping, torque constants, electrical inductance, electrical resistance, and back-emf, respectively, of the actuators. The constant transmission matrix $r\in\Re^{n\times n}$ is diagonal, $I_a\in\Re^n$ is the armature current vector, $\varphi(t)$ represents the external disturbance, $sat(\cdot)\in\Re^n$ denotes the saturation function, and $u(t)$ denotes the voltage control input. Before presenting the formulation of the control problem, we recall a useful definition:

Definition 1: The hard saturation function $sat(u_i(t),u_{i_{\max}})$ can be divided into a linear function $u_i(t)$ and a dead-zone function, $dzn(u_i(t),u_{i_{\max}})$ [2]. Thus, the control input applied to the system through the actuator is expressed as follows:

$$sat(u(t))=u(t)-dzn(u(t),u_{\max}) \tag{4}$$

where

$$sat(u(t))=\begin{bmatrix} sat(u_1(t)) \\ \vdots \\ sat(u_n(t)) \end{bmatrix}, \tag{5}$$

$$dzn(u(t),u_{\max})=\begin{bmatrix} dzn(u_1(t),u_{1_{\max}}) \\ \vdots \\ dzn(u_n(t),u_{n_{\max}}) \end{bmatrix}$$

where $dzn(\bullet)$ is the dead-zone function, and $u_{\max}$ is the maximum bound of the control input vector.

3- Proposed Controller

The presented model given by equations (1) to (3) is highly nonlinear and dynamically coupled multivariable systems that makes the control problem extremely difficult. To tackle this problem, we design a robust adaptive controller for FJEDR by employing voltage as control input signal. The process begins by designing the desired motor position θ_{md} for (1), called fictitious control signal, so that the robot dynamic can give proper performance. Then, the control signal $u(t)$ is constructed in (3) to ensure the convergence of θ_m to θ_{md} which results in a convergence of θ to the desired trajectory θ_d .

3- 1- Control Law for Robot Subsystem

Suppose that, Equation (1) can be rewritten as

$$D_i(\theta)\ddot{\theta}+C_i(\theta,\dot{\theta})\dot{\theta}+g_i(\theta)+r^{-1}\theta=\theta_m \tag{6}$$

where $D_i(\theta)=r^{-1}K^{-1}D(\theta)$, $C_i(\theta,\dot{\theta})=r^{-1}K^{-1}C(\theta,\dot{\theta})$, and $g_i(\theta)=r^{-1}K^{-1}g(\theta)$. Define an error vector as

$$S=\dot{e}+\Lambda e=\dot{\theta}-v \tag{7}$$

where $e=\theta-\theta_d$ is the link position error, $\theta_d\in\Re^n$ denotes a desired trajectory in the joint space, and $\Lambda=diag(\lambda_1,\lambda_2,\lambda_3,\dots,\lambda_n)$ with $\lambda_i>0$ for all $i=1,\dots,n$. The control problem is now to design the desired motor position θ_{md} so that θ can be converged to θ_d . Because θ_m is not a control variable, we can rewrite (6) by adding and subtracting the same term θ_{md} as follows:

$$D_i(\theta)\ddot{\theta}+C_i(\theta,\dot{\theta})\dot{\theta}+g_i(\theta)+r^{-1}\theta=\theta_{md}+e_\theta \tag{8}$$

where $e_\theta=\theta_m-\theta_{md}$ represents the motor position tracking error. Now, we define θ_{md} as

$$\theta_{md}=\hat{D}_i(\theta)\dot{v}+\hat{C}_i(\theta,\dot{\theta})v+\hat{g}_i(\theta)+r^{-1}\theta-K_D S \tag{9}$$

where $\hat{D}_i(\theta)$, $\hat{C}_i(\theta,\dot{\theta})$ and $\hat{g}_i(\theta)$ are estimates of $D_i(\theta)$, $C_i(\theta,\dot{\theta})$ and $g_i(\theta)$, respectively, and K_D is a positive diagonal gain matrix. For notational simplicity, in the sequel, we drop the argument θ and $\dot{\theta}$ from the matrices $D_i(\theta)$, $C_i(\theta,\dot{\theta})$, and from the vector $g_i(\theta)$. Next, from (9) and (8), after some manipulation it holds that

$$D_i\dot{S}+C_i S+K_D S=e_\theta-\tilde{D}_i\dot{v}-\tilde{C}_i v-\tilde{g}_i \tag{10}$$

in which $(\tilde{\bullet})=(\bullet)-(\hat{\bullet})$. If a controller $u(t)$ and some proper updating laws for $\hat{D}_i$, $\hat{C}_i$ and $\hat{g}_i$ are designed so that $\hat{D}_i\to D_i$, $\hat{C}_i\to C_i$, $\hat{g}_i\to g_i$ and $e_\theta\to 0$, (10) can give the desired performance. Toward this end, we use function approximation technique to represent D_i, C_i and g_i with the assumption that proper numbers of basis functions are employed

$$D_i(\theta)=W_{D_i}^T Z_{D_i}+\varepsilon_{D_i} \quad , \quad C_i(\theta,\dot{\theta})=W_{C_i}^T Z_{C_i}+\varepsilon_{C_i}$$
$$g_i(\theta)=W_{g_i}^T Z_{g_i}+\varepsilon_{g_i} \tag{11}$$

where $W_{D_i}\in\Re^{n^2\beta_{D_i}\times n}$, $W_{C_i}\in\Re^{n^2\beta_{C_i}\times n}$ and $W_{g_i}\in\Re^{n\beta_{g_i}\times n}$ are weighting matrices and $Z_{D_i}\in\Re^{n^2\beta_{D_i}\times n}$, $Z_{C_i}\in\Re^{n^2\beta_{C_i}\times n}$ and $Z_{g_i}\in\Re^{n\beta_{g_i}}$ are matrices of basis functions. The number $\beta_{(i)}$ represents the number of basis functions used. Using the same set of basis functions, the corresponding estimates can also be represented as

$$\hat{D}_i(\theta)=\hat{W}_{D_i}^T Z_{D_i} \quad , \quad \hat{C}_i(\theta,\dot{\theta})=\hat{W}_{C_i}^T Z_{C_i}$$
$$\hat{g}_i(\theta)=\hat{W}_{g_i}^T Z_{g_i} \tag{12}$$

Therefore, the right-hand side of (9) can be written as

$$\theta_{md} = \hat{W}_{D_i}^T Z_{D_i} \dot{\nu} + \hat{W}_{C_i}^T Z_{C_i} \nu + \hat{W}_{g_i}^T Z_{g_i} + r^{-1}\theta - K_D S \quad (13)$$

Now, combining equations (8) and (13), we have an error equation of the form

$$D_i \dot{S} + C_i S + K_D S = e_\theta - \tilde{W}_{D_i}^T Z_{D_i} \dot{\nu} - \tilde{W}_{C_i}^T Z_{C_i} \nu - \tilde{W}_{g_i}^T Z_{g_i} + \varepsilon_1 \quad (14)$$

where $\varepsilon_1 = \varepsilon_1(\varepsilon_{D_i}, \varepsilon_{C_i}, \varepsilon_{g_i}, \nu)$ is the lumped approximation error vector.

3- 2- Control Law for Motor Subsystem

Here, the control objective is to design a control input $u(t)$ to realize the perfect motor position vector in (13), such that e_θ can either converge to zero or at least be bounded. It refers to the fact that a constant-bounded disturbance will not destroy the stability result under robust control θ_{md} which is a result of uniform ultimate boundedness of tracking error using Lyapunov-based theory of guaranteed stability of uncertain systems [10]. With this in mind, the control input is introduced as

$$u(t) = \hat{K}_b(\dot{\theta}_{md} - \alpha e_\theta) + \hat{\eta}(t) \quad (15)$$

where $\hat{K}_b$ is the positive diagonal constant matrix representing an estimation of K_b, α is a positive constant gain matrix, and $\hat{\eta}(t)$ is the estimation of $\eta(t)$ called residual uncertain denoted by

$$\eta(t) = L\dot{I}_a(t) + RI_a(t) - (\hat{K}_b - K_b)\dot{\theta}_m(t) + \varphi(t) + dzn(u(t), u_{\max}) \quad (16)$$

With Inserting (15) into (3) and from (4), after some manipulation it holds that

$$\hat{K}_b(\dot{e}_\theta + \alpha e_\theta) = \hat{\eta}(t) - \eta(t) \quad (17)$$

If an appropriate updating law for $\eta(t)$ can be designed, we may ensure $e_\theta \to 0$ as time goes to infinity. Toward this end, we apply the function approximation representation for $\eta(t)$ as

$$\eta(t) = W_\eta^T Z_\eta + \varepsilon_\eta \quad (18)$$

where $W_\eta \in \Re^{n\beta_\eta \times n}$ is weighting matrix, $Z_\eta \in \Re^{n\beta_\eta}$ is the matrix of basis function, and ε_η is the vector of lumped approximation error. In addition, the corresponding estimate of the last equation is represented by

$$\hat{\eta}(t) = \hat{W}_\eta^T Z_\eta \quad (19)$$

Thus, equation (17) can be rewritten as

$$\hat{K}_b(\dot{e}_\theta + \alpha e_\theta) = -\tilde{W}_\eta^T Z_\eta + \varepsilon_\eta \quad (20)$$

4- Stability Analysis and Performance Evaluation

To analyze the stability of the overall system that has saturation elements in the actuators, we need the two following Assumptions.

Assumption 1. The desired reference trajectory is assumed to be bounded and uniformly continuous, and has bounded and uniformly continuous derivatives up to a necessary order.

Assumption 2. $\dot{\theta}_m$, I_a, and $\dot{I}_a$ are bounded since the control input vector is bounded [25].

4- 1- Stability analysis

To carry out the stability analysis of the closed-loop system formed by the robot dynamic models (1) - (3) together with the controllers (13) and (15), a Lyapunov-like function is devised as:

$$V(S, e_\theta, \tilde{W}_{D_i}, \tilde{W}_{C_i}, \tilde{W}_{g_i}, \tilde{W}_\eta) = \frac{1}{2}S^T D_i S + \frac{1}{2}e_\theta^T \hat{K}_b e_\theta + \frac{1}{2}Tr(\tilde{W}_{D_i}^T Q_{D_i} \tilde{W}_{D_i} + \tilde{W}_{C_i}^T Q_{C_i} \tilde{W}_{C_i} + \tilde{W}_{g_i}^T Q_{g_i} \tilde{W}_{g_i} + \tilde{W}_\eta^T Q_\eta \tilde{W}_\eta) \quad (21)$$

where $Tr(\bullet)$ is the trace operator; $Q_{D_i} \in \Re^{n^2\beta_{D_i} \times n^2\beta_{D_i}}$, $Q_{C_i} \in \Re^{n^2\beta_{C_i} \times n^2\beta_{C_i}}$, $Q_{g_i} \in \Re^{n\beta_{g_i} \times n\beta_{g_i}}$ and $Q_\eta \in \Re^{n\beta_\eta \times n\beta_\eta}$ are positive definite weighting matrices related to the adaption laws. The last function has the following upper and lower bound which is crucial within the analytical setting in this work:

$$V \le \frac{1}{2}[\lambda_{\max}(A)\left\|\begin{bmatrix} S \\ e_\theta \end{bmatrix}\right\|^2 + \lambda_{\max}(Q_{D_i})Tr(\tilde{W}_{D_i}^T \tilde{W}_{D_i}) + \lambda_{\max}(Q_{C_i})Tr(\tilde{W}_{C_i}^T \tilde{W}_{C_i}) + \lambda_{\max}(Q_{g_i})Tr(\tilde{W}_{g_i}^T \tilde{W}_{g_i}) + \lambda_{\max}(Q_\eta)Tr(\tilde{W}_\eta^T \tilde{W}_\eta)] \quad (22)$$

$$V \ge \frac{1}{2}[\lambda_{\min}(A)\left\|\begin{bmatrix} S \\ e_\theta \end{bmatrix}\right\|^2 + \lambda_{\min}(Q_{D_i})Tr(\tilde{W}_{D_i}^T \tilde{W}_{D_i}) + \lambda_{\min}(Q_{C_i})Tr(\tilde{W}_{C_i}^T \tilde{W}_{C_i}) + \lambda_{\min}(Q_{g_i})Tr(\tilde{W}_{g_i}^T \tilde{W}_{g_i}) + \lambda_{\min}(Q_\eta)Tr(\tilde{W}_\eta^T \tilde{W}_\eta)] \quad (23)$$

where

$$A = \begin{bmatrix} D_i & 0 \\ 0 & \hat{K}_b \end{bmatrix}.$$

Using the property $\dot{D}_i(\theta) - 2C_i(\theta, \dot{\theta}) = 0$, the time derivative of (21) along the trajectories of systems (14) and (20) is

$$\dot{V} = -S^T K_D S - e_\theta^T \hat{K}_b \alpha e_\theta + S^T e_\theta + S^T \varepsilon_1 + e_\theta^T \varepsilon_\eta - Tr[\tilde{W}_{D_i}^T(Q_{D_i}\dot{\hat{W}}_{D_i} + Z_{D_i}\dot{\nu}S^T)] - Tr[\tilde{W}_{C_i}^T(Q_{C_i}\dot{\hat{W}}_{C_i} + Z_{C_i}\nu S^T)] - Tr[\tilde{W}_{g_i}^T(Q_{g_i}\dot{\hat{W}}_{g_i} + Z_{g_i}S^T)] - Tr[\tilde{W}_\eta^T(Q_\eta\dot{\hat{W}}_\eta + Z_\eta e_\theta^T)] \quad (24)$$

Let us select the update laws with σ-modification as:

$$\begin{aligned} \dot{\hat{W}}_{D_i} &= -Q_{D_i}^{-1}(Z_{D_i}\dot{\nu}S^T + \sigma_{D_i}\hat{W}_{D_i}) \\ \dot{\hat{W}}_{C_i} &= -Q_{C_i}^{-1}(Z_{C_i}\nu S^T + \sigma_{C_i}\hat{W}_{C_i}) \\ \dot{\hat{W}}_{g_i} &= -Q_{g_i}^{-1}(Z_{g_i}S^T + \sigma_{g_i}\hat{W}_{g_i}) \\ \dot{\hat{W}}_\eta &= -Q_\eta^{-1}(Z_\eta e_\theta^T + \sigma_\eta\hat{W}_\eta) \end{aligned} \quad (25)$$

where $\sigma_{(\cdot)}$ are positive numbers. Thus, equation (24) can be rewritten as:

$$\dot{V} = -\begin{bmatrix} S^T & e_\theta^T \end{bmatrix} P \begin{bmatrix} S \\ e_\theta \end{bmatrix} + \begin{bmatrix} S^T & e_\theta^T \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_\eta \end{bmatrix} + \sigma_{D_i} Tr(\tilde{W}_{D_i}^T \hat{W}_{D_i}) + \sigma_{C_i} Tr(\tilde{W}_{C_i}^T \hat{W}_{C_i}) + \sigma_{g_i} Tr(\tilde{W}_{g_i}^T \hat{W}_{g_i}) + \sigma_\eta Tr(\tilde{W}_\eta^T \hat{W}_\eta) \quad (26)$$

Where

$$P = \begin{bmatrix} K_D & -0.5I \\ -0.5I & \hat{K}_b \alpha \end{bmatrix} \quad (27)$$

The two following conditions guarantee that the matrix P is positive definite,

$$K_D > 0 \quad , \quad K_D \hat{K}_b \alpha > 0.25I \quad (28)$$

Remark 1. Suppose that a sufficient number of basis functions are used and the approximation error can be ignored, then it is not necessary to include the σ-modification terms in (25). Hence, (26) can be reduced to

$$\dot{V} = -\begin{bmatrix} S^T & e_\theta^T \end{bmatrix} P \begin{bmatrix} S \\ e_\theta \end{bmatrix} \le 0 \quad (29)$$

and convergence of S and e_θ can be further proved by Barbalat's Lemma.

Remark 2. Owing to the existence of ε_1 and ε_η in (26), the negative definiteness of $\dot{V}$ cannot be determined. In the following, we will investigate the closed-loop stability in the presence of these approximation errors. It is very easy to prove that

$$-\begin{bmatrix} S^T & e_\theta^T \end{bmatrix} P \begin{bmatrix} S \\ e_\theta \end{bmatrix} + \begin{bmatrix} S^T & e_\theta^T \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} \le -\frac{1}{2}\left(\lambda_{\min}(P) \left\| \begin{bmatrix} S \\ e_\theta \end{bmatrix} \right\|^2 - \frac{1}{\lambda_{\min}(P)} \left\| \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} \right\|^2 \right) \quad (30)$$

$$Tr(\tilde{W}_{(\cdot)}^T \hat{W}_{(\cdot)}) \le \frac{1}{2} Tr(W_{(\cdot)}^T W_{(\cdot)}) - \frac{1}{2} Tr(\tilde{W}_{(\cdot)}^T \tilde{W}_{(\cdot)})$$

Together with the relationship and using (22), we may rewrite equation (26) as

$$\begin{aligned} \dot{V} \le & -\delta V + \frac{1}{2}[\delta \lambda_{\max}(A) - \lambda_{\min}(P)] \left\| \begin{bmatrix} S \\ e_\theta \end{bmatrix} \right\|^2 + \frac{1}{2\lambda_{\min}(P)} \left\| \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} \right\|^2 \\ & + \frac{1}{2}\left[\delta \lambda_{\max}(Q_{D_i}) - \sigma_{D_i} \right] Tr(\tilde{W}_{D_i}^T \tilde{W}_{D_i}) \\ & + \frac{1}{2}\left[\delta \lambda_{\max}(Q_{C_i}) - \sigma_{C_i} \right] Tr(\tilde{W}_{C_i}^T \tilde{W}_{C_i}) \\ & + \frac{1}{2}\left[\delta \lambda_{\max}(Q_{g_i}) - \sigma_{g_i} \right] Tr(\tilde{W}_{g_i}^T \tilde{W}_{g_i}) \\ & + \frac{1}{2}\left[\delta \lambda_{\max}(Q_\eta) - \sigma_\eta \right] Tr(\tilde{W}_\eta^T \tilde{W}_\eta) \\ & + \frac{1}{2}\left[\sigma_{D_i} Tr(W_{D_i}^T W_{D_i}) + \sigma_{C_i} Tr(W_{C_i}^T W_{C_i}) + \sigma_{g_i} Tr(W_{g_i}^T W_{g_i}) + \sigma_\eta Tr(W_\eta^T W_\eta) \right] \end{aligned} \quad (31)$$

where δ is a constant to be selected as

$$\delta \le \min\left\{ \frac{\lambda_{\min}(P)}{\lambda_{\max}(A)}, \frac{\sigma_{D_i}}{\lambda_{\max}(Q_{D_i})}, \frac{\sigma_{C_i}}{\lambda_{\max}(Q_{C_i})}, \frac{\sigma_{g_i}}{\lambda_{\max}(Q_{g_i})}, \frac{\sigma_\eta}{\lambda_{\max}(Q_\eta)} \right\} \quad (32)$$

Then, (31) becomes

$$\dot{V} \le -\delta V + \frac{1}{2\lambda_{\min}(P)} \left\| \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} \right\|^2 + \frac{1}{2}[\sigma_{D_i} Tr(W_{D_i}^T W_{D_i}) + \sigma_{C_i} Tr(W_{C_i}^T W_{C_i}) + \sigma_{g_i} Tr(W_{g_i}^T W_{g_i}) + \sigma_\eta Tr(W_\eta^T W_\eta)] \quad (33)$$

This implies $\dot{V} < 0$ whenever

$$V > \frac{1}{2\delta \lambda_{\min}(P)} \sup_{\tau \ge t_0} \left\| \begin{bmatrix} \varepsilon_1(\tau) \\ \varepsilon_2(\tau) \end{bmatrix} \right\|^2 + \frac{1}{2\delta}[\sigma_{D_i} Tr(W_{D_i}^T W_{D_i}) + \sigma_{C_i} Tr(W_{C_i}^T W_{C_i}) + \sigma_{g_i} Tr(W_{g_i}^T W_{g_i}) + \sigma_\eta Tr(W_\eta^T W_\eta)] \quad (34)$$

Hence, we have proved that S , e_θ, $\tilde{W}_{D_i}$, $\tilde{W}_{C_i}$, $\tilde{W}_{g_i}$ and $\tilde{W}_\eta$ are uniformly ultimately bounded.

4- 2- performance evaluation

From (33), we compute the upper bound for $V(t)$ as

$$V(t) \le e^{-\delta(t-t_0)} V(t_0) + \frac{1}{2\delta \lambda_{\min}(P)} \sup_{t_0 < \tau < t} \left\| \begin{bmatrix} \varepsilon_1(\tau) \\ \varepsilon_2(\tau) \end{bmatrix} \right\|^2 + \frac{1}{2\delta}[\sigma_{D_i} Tr(W_{D_i}^T W_{D_i}) + \sigma_{C_i} Tr(W_{C_i}^T W_{C_i}) + \sigma_{g_i} Tr(W_{g_i}^T W_{g_i}) + \sigma_\eta Tr(W_\eta^T W_\eta)] \quad (35)$$

Using the inequality (23), we find the upper bound for $\left\| \begin{bmatrix} S^T & e_\theta^T \end{bmatrix}^T \right\|^2$ as

$$\left\| \begin{bmatrix} S \\ e_\theta \end{bmatrix} \right\|^2 \le \frac{2}{\lambda_{\min}(A)} e^{-\delta(t-t_0)} V(t_0) + \frac{1}{\delta \lambda_{\min}(A) \lambda_{\min}(P)} \sup_{t_0 < \tau < t} \left\| \begin{bmatrix} \varepsilon_1(\tau) \\ \varepsilon_2(\tau) \end{bmatrix} \right\|^2 + \frac{1}{\delta \lambda_{\min}(A)}[\sigma_{D_i} Tr(W_{D_i}^T W_{D_i}) + \sigma_{C_i} Tr(W_{C_i}^T W_{C_i}) + \sigma_{g_i} Tr(W_{g_i}^T W_{g_i}) + \sigma_\eta Tr(W_\eta^T W_\eta)] \quad (36)$$

Therefore, we compute the bound as

$$\begin{aligned}\left\|\begin{bmatrix}S\\ e_\theta\end{bmatrix}\right\| &\le \sqrt{\frac{2V(t_0)}{\lambda_{\min}(A)}}\,e^{\frac{-\delta(t-t_0)}{2}} \\ &+\frac{1}{\sqrt{\delta\lambda_{\min}(A)\lambda_{\min}(P)}}\sup_{t_0<\tau<t}\left\|\begin{bmatrix}\varepsilon_1(\tau)\\ \varepsilon_2(\tau)\end{bmatrix}\right\| \\ &+\frac{1}{\sqrt{\delta\lambda_{\min}(A)}}[\sigma_{D_i}Tr(W_{D_i}^T W_{D_i})+\sigma_{C_i}Tr(W_{C_i}^T W_{C_i}) \\ &\quad +\sigma_{g_i}Tr(W_{g_i}^T W_{g_i})+\sigma_\eta Tr(W_\eta^T W_\eta)]^{\frac{1}{2}}\end{aligned} \tag{37}$$

This implies that the magnitude of the S and motor position errors are bounded by an exponential function plus some constants. This also implies that by adjusting controller parameters, we can improve output error convergence rate. As a consequence,

$$\begin{aligned}\lim_{t\to\infty}\left\|\begin{bmatrix}S\\ e_\theta\end{bmatrix}\right\| &\le \frac{1}{\sqrt{\delta\lambda_{\min}(A)\lambda_{\min}(P)}}\sup_{t_0<\tau<t}\left\|\begin{bmatrix}\varepsilon_1(\tau)\\ \varepsilon_2(\tau)\end{bmatrix}\right\| \\ &+\frac{1}{\sqrt{\delta\lambda_{\min}(A)}}[\sigma_{D_i}Tr(W_{D_i}^T W_{D_i})+\sigma_{C_i}Tr(W_{C_i}^T W_{C_i}) \\ &+\sigma_{g_i}Tr(W_{g_i}^T W_{g_i})+\sigma_\eta Tr(W_\eta^T W_\eta)]^{\frac{1}{2}}\end{aligned} \tag{38}$$

The transient performance analysis is thus completed.

Using Assumption (1) and boundedness of $\left\|\begin{bmatrix}S\\ e_\theta\end{bmatrix}\right\|$, it can be concluded from the equation (9) that θ_{md} is bounded since θ, $\dot{\theta}$, $\hat{D}_i(\theta)$, $\hat{C}_i(\theta,\dot{\theta})$ and $\hat{g}_i(\theta)$ are all bounded. Moreover, θ_m is bounded since e_θ and θ_{md} are bounded. These results in addition to Assumption 2, yield boundedness of all the system's states. The validity of the proposed approach will be verified with the experimental results on a single-link FJEDR.

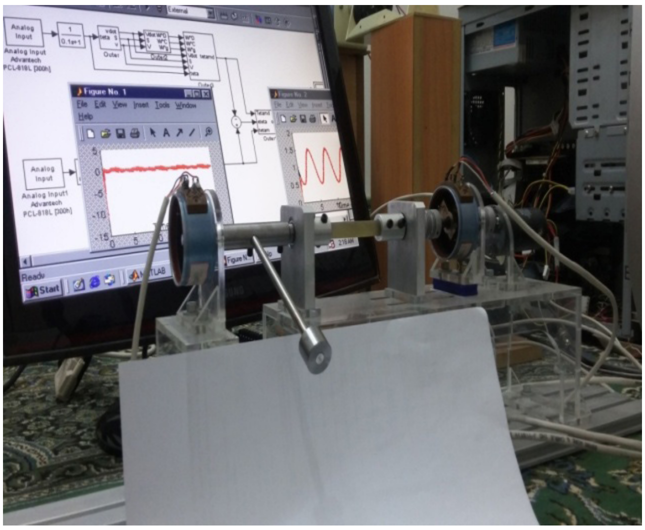

Figure 1. Experimental setup

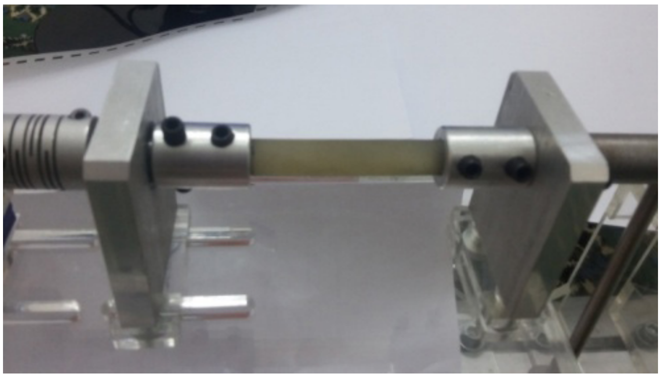

Figure 2.The flexible element

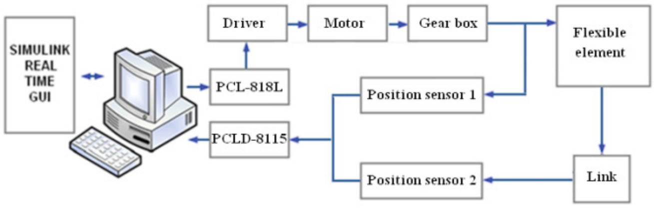

Figure 3. Block diagram of the system

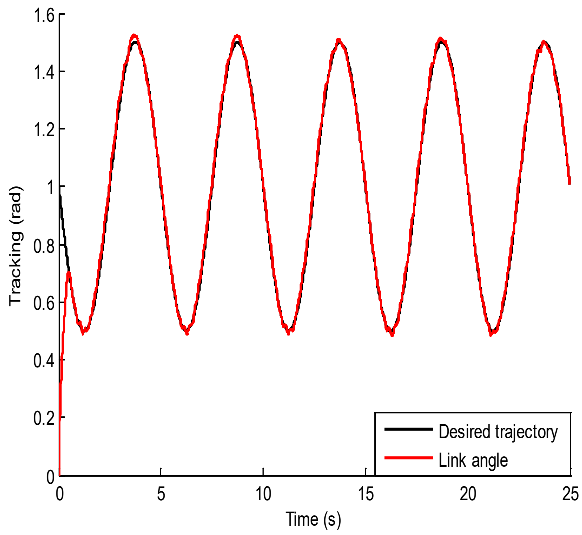

Figure 4. Output tracking performance

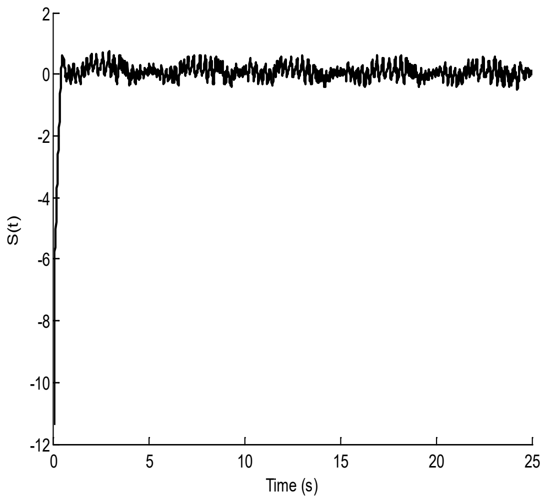

Figure 5. Filtered tracking error

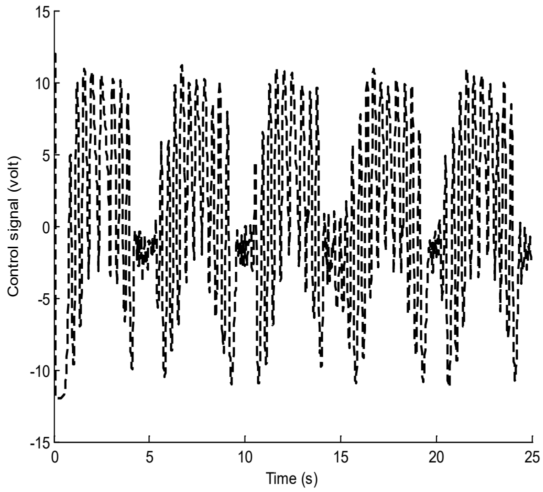

Figure 6. Control signal

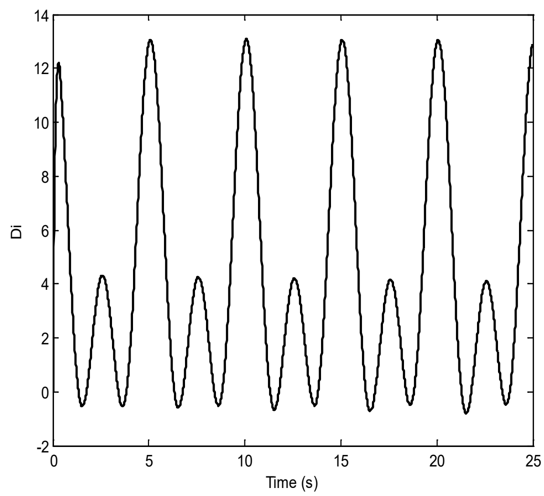

Figure 7. Approximation of D_i

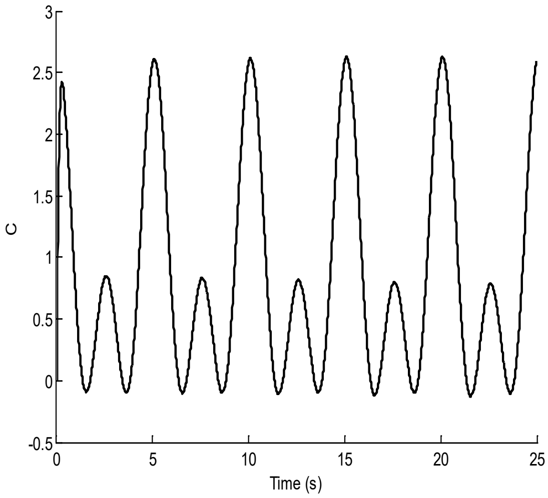

Figure 8. Approximation of C_i

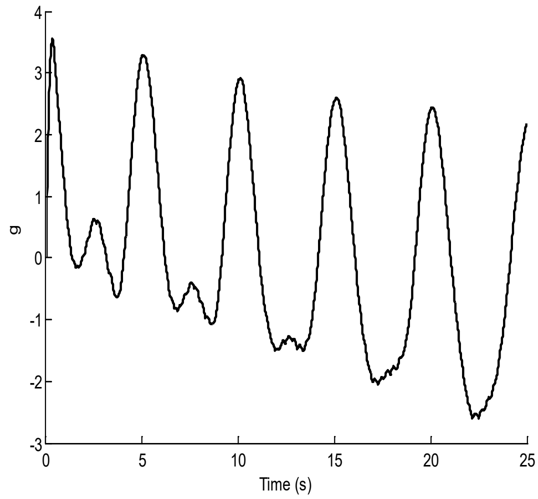

Figure 9.Approximation of g_i

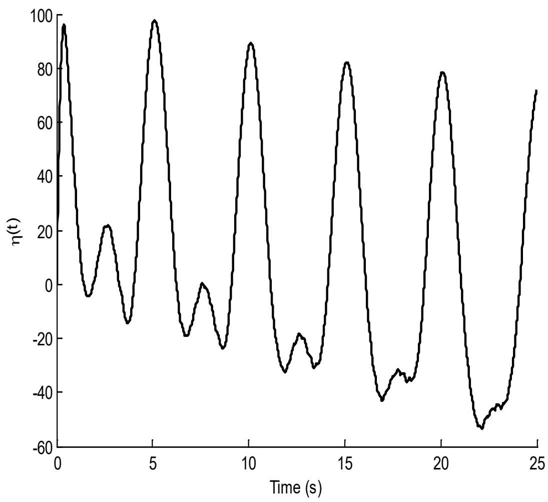

Figure 10. Approximation of η

5- Experimental Study

In this section, experiments are conducted to test the performance of the proposed control strategy. A photograph of the experimental setup, that is a single-link flexible joint manipulator, is illustrated in Fig. 1. The flexible element utilized for power transmission system is shown in Fig. 2. It has been made from polyurethane and is designed so that it has a very high flexibility. One end of the flexible element is directly coupled to a geared permanent magnet DC motor (characterized by Barber-Colman Company operating within ±12 volt input) that is driven by a pulse-width modulation (PWM) driver. The other end is connected to a steel arm. Two potentiometers are installed to provide the feedbacks from the motor and the arm angles. The measured input-output data are transferred to the computer (Pentium II 366 MHz) by a data acquisition card with the trademark ADVANTECH PCLD-818L. It can sample the analog data with the maximum sampling rate of 100 kHz. Also, this card has a built-in 12-bit high-speed A/D converter with the maximum conversion rate of 40 kHz. The data acquisition card allows us to control the practical manipulator through user-defined programs in MATLAB/SIMULINK environment. The proposed controller is implemented in a timer-interrupt service routine with the 10-ms sampling rate. A block diagram of the system is shown in Fig. 3. The reference trajectory is a sinusoid wave defined as $\theta_d(t) = 1 - 0.5\sin(0.4\pi t)$. The controller parameters were selected as

$$K_D = 200\ ,\ \hat{K}_b = 0.26\ ,\ \alpha = 10\ ,\ \Lambda = 10. \tag{39}$$

We assume that the system parameters and their variation bounds are not known. Let us select the five first terms of Fourier series as the basis function for the approximation. Therefore, $\hat{W}_{D_i}$, $\hat{W}_{C_i}$, $\hat{W}_{g_i}$ and $\hat{W}_{\eta}$ are in $\Re^5$. The initial weighting vectors for the entries are also assigned to zero. The gained matrices in the updating laws are selected as

$$Q_{D_i} = Q_{C_i} = Q_{\eta_i} = 10 I_5 \quad , \quad Q_{g_i} = I_5 \tag{40}$$

In this step, we assume that the approximation error can be neglected, and hence the σ-modification parameters are chosen as $\sigma_{(\cdot)} = 0$. Under these settings, the link trajectory is then shown in Fig.4. According to these figures, the link angle converges to its desired value with a fast transient response, in spite of large initial tracking error. The filtered tracking error (7) is also plotted in Fig. 5, which is negligible. The applied voltage to the motor is given in Fig. 6. Figs. 7 to 10 illustrate the functions' approximations, which are bounded as desired. Thus, the proposed controller can overcome the system nonlinearities and shows acceptable robustness against various uncertainties.

6- Conclusion

This paper presented a robust adaptive controller for FJEDR considering uncertainties in the both actuator and manipulator dynamics. The controller design is not dependent on the mechanical dynamics of the actuators, thus, it is free from problems associated with torque control strategy in the design and implementation. It was shown that the closed-loop system has BIBO stability while it obtains uniformly ultimately bounded (UUB) stability of link/actuator position tracking error based on the direct method of Lyapunov. Experimental results verified the successful practical implementation of the proposed control strategy. Experimental results showed that tracking performance is satisfactory such that the effects of joint flexibility are well under control. The performance of the control system indicated that the control system is robust against all uncertainties in the manipulator dynamics and its motors. Moreover, motor voltages is permitted under the maximum value.

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