Design Baseline Computed Torque Controller

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Abstract

The application of design nonlinear controller such as computed torque controller in control of 6 degrees of freedom (DOF) robot arm will be investigated in this research. One of the significant challenges in control algorithms is a linear behavior controller design for nonlinear systems (e.g., robot manipulator). Some of robot manipulators which work in industrial processes are controlled by linear PID controllers, but the design of linear controller for robot manipulators is extremely difficult because they are hardly nonlinear and uncertain. To reduce the above challenges, the nonlinear robust controller is used to control of robot manipulator. Computed torque controller is a powerful nonlinear controller under condition of partly uncertain dynamic parameters of system. This controller is used to control of highly nonlinear systems especially for robot manipulators. To adjust this controller's coefficient baseline methodology is used and applied to CTC.

Keywords: Baseline Tuning Computed Torque Controller, Computed Torque Controller, Unstructured Model Uncertainties, Adaptive Method.

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1. INTRODUCTION and MOTIVATION

PUMA 560 robot manipulator is a 6 DOF serial robot manipulator. From the control point of view, robot manipulator divides into two main parts i.e. kinematics and dynamic parts. Controller is a device which can sense information from linear or nonlinear system (e.g., robot manipulator) to improve the systems performance [1-4]. The main targets in designing control systems are stability, good disturbance rejection, and small tracking error[5-6]. Several industrial robot manipulators are controlled by linear methodologies (e.g., Proportional-Derivative (PD) controller, Proportional- Integral (PI) controller or Proportional- Integral-Derivative (PID) controller), but when robot manipulator works with various payloads and have uncertainty in dynamic models this technique has limitations. In some applications robot manipulators are used in an unknown and unstructured environment, therefore strong mathematical tools used in new control methodologies to design nonlinear robust controller with an acceptable performance (e.g., minimum error, good trajectory, disturbance rejection). Computed torque controller (CTC) is an influential nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known the controller works superbly; practically a large amount of systems have uncertainties and sliding mode controller reduce this kind of limitation [7]. This controller is used to control of highly nonlinear systems especially for robot manipulators. In various dynamic parameters systems that need to be training on-line adaptive control methodology is used.

Background

Computed torque controller (CTC) is a powerful nonlinear controller which it widely used in control robot manipulator. It is based on Feed-back linearization and computes the required arm torques using the nonlinear feedback control law. This controller works very well when all dynamic and physical parameters are known but when the robot manipulator has variation in dynamic parameters, in this situation the controller has no acceptable performance[14]. In practice, most of physical systems (e.g., robot manipulators) parameters are unknown or time variant, therefore, computed torque like controller used to compensate dynamic equation of robot manipulator[1, 6]. Research on computed torque controller is significantly growing on robot manipulator application which has been reported in [1, 6, 15-16]. Vivas and Mosquera [15]have proposed a predictive functional controller and compare to computed torque controller for tracking response in uncertain environment. However both controllers have been used in Feed-back linearization, but predictive strategy gives better result as a performance. A computed torque control with non parametric regression models have been presented for a robot arm[16]. This controller also has been problem in uncertain dynamic models. Based on [1, 6]and [15-16]Computed torque controller is a significant nonlinear controller to certain systems which it is based on feedback linearization and computes the required arm torques using the nonlinear feedback control law. When all dynamic and physical parameters are known the controller works fantastically; practically a large amount of systems have uncertainties and sliding mode controller decrease this kind of challenge.

2. THEOREM: DYNAMIC FORMULATION OF ROBOTIC MANIPULATOR, COMPUTED TORQUE FORMULATION AND APPLIED TO ROBOT ARM

Dynamic of robot arm: The equation of an *n-DOF* robot manipulator governed by the following equation [1, 4, 15]:

$$M(q)\ddot{q} + N(q,\dot{q}) = \tau \tag{1}$$

Where τ is actuation torque, M (q) is a symmetric and positive define inertia matrix, $N(q,\dot{q})$ is the vector of nonlinearity term. This robot manipulator dynamic equation can also be written in a following form [1-29]:

$$\tau = M(q)\ddot{q} + B(q)[\dot{q}\,\dot{q}] + C(q)[\dot{q}]^2 + G(q) \tag{2}$$

Where B(q) is the matrix of coriolios torques, C(q) is the matrix of centrifugal torques, and G(q) is the vector of gravity force. The dynamic terms in equation (2) are only manipulator position. This is a decoupled system with simple second order linear differential dynamics. In other words, the component $\ddot{q}$ influences, with a double integrator relationship, only the joint variableq_i, independently of the motion of the other joints. Therefore, the angular acceleration is found as to be [3, 15-62]:

$$\ddot{q} = M^{-1}(q).\{\tau - N(q,\dot{q})\} \tag{3}$$

This technique is very attractive from a control point of view.

Computed Torque Controller

The central idea of computed torque controller (CTC) is feedback linearization. Originally this algorithm is called feedback linearization method. It has assumed that the desired motion trajectory for the manipulator $q_d(t)$, as determined, by a path planner. Defines the tracking error as:

$$e(t) = q_d(t) - q_a(t) \tag{4}$$

Where e(t) is error of the plant, $q_d(t)$ is desired input variable, that in our system is desired displacement, $q_a(t)$ is actual displacement. If an alternative linear state-space equation in the form $\dot{x} = Ax + BU$ can be defined as

$$\dot{x} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ I \end{bmatrix} U \tag{5}$$

With $U = -M^{-1}(q).N(q,\dot{q}) + M^{-1}(q).\tau$ and this is known as the Brunousky canonical form. By equation (4) and (5) the Brunousky canonical form can be written in terms of the state $x = [e^T \ \dot{e}^T]^T$ as [1]:

$$\frac{d}{dt}\begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}.\begin{bmatrix} e \\ \dot{e} \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} U \tag{6}$$

With

$$U = \ddot{q}_d + M^{-1}(q).\{N(q,\dot{q}) - \tau\} \tag{7}$$

Then compute the required arm torques using inverse of equation (7), is;

$$\tau = M(q)(\ddot{q}_d - U) + N(\dot{q},q) \tag{8}$$

This is a nonlinear feedback control law that guarantees tracking of desired trajectory. Selecting proportional-plus-derivative (PD) feedback for U(t) results in the PD-computed torque controller [6];

$$\tau = M(q)\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) + N(q,\dot{q}) \tag{9}$$

and the resulting linear error dynamics are

$$\left(\ddot{q}_d + K_v\dot{e} + K_p e\right) = 0 \tag{10}$$

According to the linear system theory, convergence of the tracking error to zero is guaranteed [6]. Where K_p and K_v are the controller gains. The result schemes is shown in Figure 1, in which two feedback loops, namely, inner loop and outer loop, which an inner loop is a compensate loop and an outer loop is a tracking error loop.

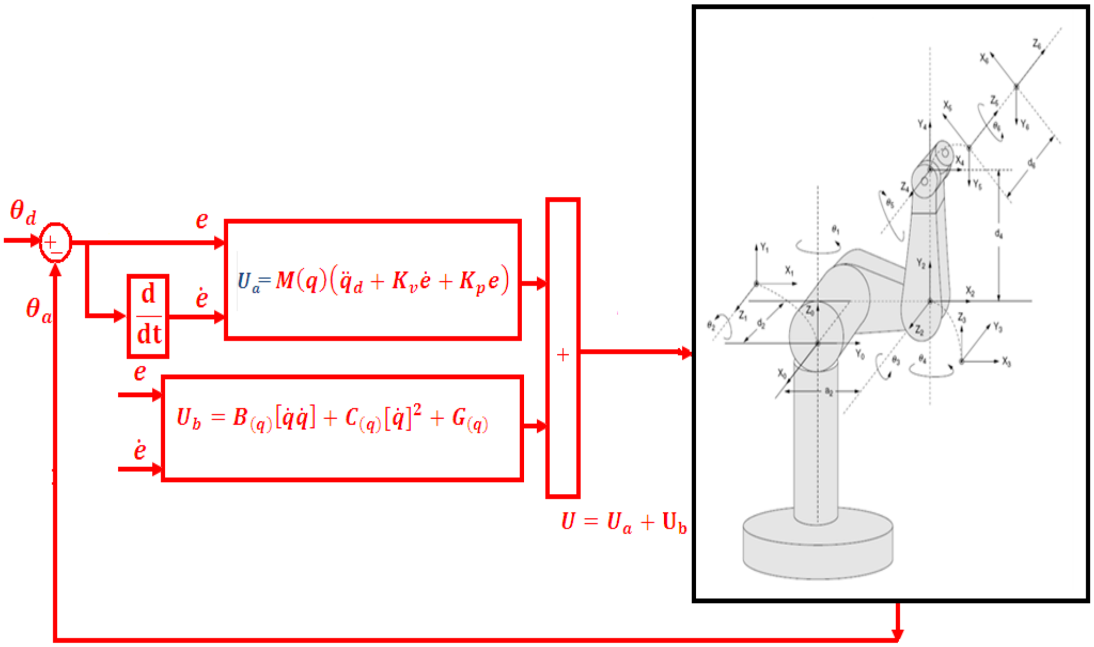

FIGURE 1: Block diagram of PD-computed torque controller (PD-CTC)

The application of proportional-plus-derivative (PD) computed torque controller to control of PUMA 560 robot manipulator introduced in this part. Suppose that in (9) the nonlinearity term defined by the following term;

$$N(q,\dot{q}) = B(q)\dot{q}\dot{q} + C(q)\dot{q}^2 + g(q) = \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\ 2} + C_{13}\dot{q}_3^{\ 2} \\ C_{21}\dot{q}_1^{\ 2} + C_{23}\dot{q}_3^{\ 2} \\ C_{31}\dot{q}_1^{\ 2} + C_{32}\dot{q}_2^{\ 2} \\ 0 \\ C_{51}\dot{q}_1^{\ 2} + C_{52}\dot{q}_2^{\ 2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \tag{11}$$

Therefore the equation of PD-CTC for control of PUMA 560 robot manipulator is written as the equation of (12);

$$\begin{bmatrix} \widehat{\tau_1} \\ \widehat{\tau_2} \\ \widehat{\tau_3} \\ \widehat{\tau_4} \\ \widehat{\tau_5} \\ \widehat{\tau_6} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & 0 & 0 & 0 \\ M_{21} & M_{22} & M_{23} & 0 & 0 & 0 \\ M_{31} & M_{32} & M_{33} & 0 & M_{35} & 0 \\ 0 & 0 & 0 & M_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & M_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{66} \end{bmatrix} \begin{bmatrix} \ddot{q}_{d1} + K_{v1}\dot{e}_1 + K_{p1}e_1 \\ \ddot{q}_{d2} + K_{v2}\dot{e}_2 + K_{p2}e_2 \\ \ddot{q}_{d3} + K_{v3}\dot{e}_3 + K_{p3}e_3 \\ \ddot{q}_{d4} + K_{v4}\dot{e}_4 + K_{p4}e_4 \\ \ddot{q}_{d5} + K_{v5}\dot{e}_5 + K_{p5}e_5 \\ \ddot{q}_{d6} + K_{v6}\dot{e}_6 + K_{p6}e_6 \end{bmatrix} + \begin{bmatrix} b_{112}\dot{q}_1\dot{q}_2 + b_{113}\dot{q}_1\dot{q}_3 + 0 + b_{123}\dot{q}_2\dot{q}_3 \\ 0 + b_{223}\dot{q}_2\dot{q}_3 + 0 + 0 \\ 0 \\ b_{412}\dot{q}_1\dot{q}_2 + b_{413}\dot{q}_1\dot{q}_3 + 0 + 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} C_{12}\dot{q}_2^{\ 2} + C_{13}\dot{q}_3^{\ 2} \\ C_{21}\dot{q}_1^{\ 2} + C_{23}\dot{q}_3^{\ 2} \\ C_{31}\dot{q}_1^{\ 2} + C_{32}\dot{q}_2^{\ 2} \\ 0 \\ C_{51}\dot{q}_1^{\ 2} + C_{52}\dot{q}_2^{\ 2} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ g_2 \\ g_3 \\ 0 \\ g_5 \\ 0 \end{bmatrix} \tag{12}$$

The controller based on a formulation (12) is related to robot dynamics therefore it has problems in uncertain conditions.

3. METHODOLOGY: BASELINE ON-LINE TUNING FOR STABLE COMPUTED TORQUE CONTROLLER

Computed torque controller has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining CTC and baseline tuning method which this method can helps to improve the system's tracking performance by online tuning method. In this research the nonlinear equivalent dynamic (equivalent part) formulation problem in uncertain system is solved by using on-line linear error-based tuning theorem. In this method linear theorem is applied to CTC to adjust the coefficient. CTC has difficulty in handling unstructured model uncertainties and this controller's performance is sensitive to controller coefficient. It is possible to solve above challenge by combining linear error-based tuning method and CTC. Based on above discussion, compute the best value of controller coefficient has played important role to improve system's tracking performance especially when the system parameters are unknown or uncertain. This problem is solved by tuning the controller coefficient of the CTC continuously in real-time. In this methodology, the system's performance is improved with respect to the pure CTC. Figure 2 shows the baseline tuning CTC. Based on (23) and (27) to adjust the controller coefficient we define $\hat{f}(x|K)$ as the baseline tuning.

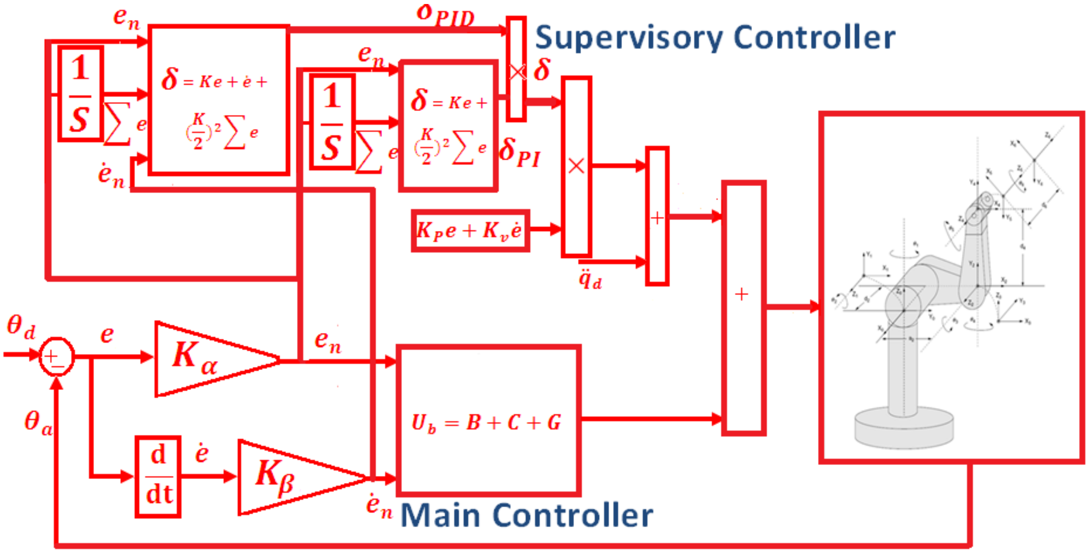

FIGURE 2: Block diagram of a baseline computed torque controller

$$\hat{f}(x|K) = K^T \delta \tag{13}$$

If minimum error (K^*) is defined by;

$$K^* = arg\ min\ [(Sup\left|\hat{f}(x|K) - f(x)\right)] \tag{14}$$

Where K^T is adjusted by an adaption law and this law is designed to minimize the error's parameters of $K - K^*$. adaption law in linear error-based tuning CTC is used to adjust the controller coefficient. Linear error-based tuning part is a supervisory controller based on the following formulation methodology. This controller has three inputs namely; error (e), change of error ($\dot{e}$) and the integral of error ($\sum e$) and an output namely; gain updating factor(δ). As a summary design a linear error-based tuning is based on the following formulation:

$$\delta = (A.e + \dot{e} + \frac{(A)^2}{2} \sum e) \times (A.e + \frac{(A)^2}{2} \sum e) \tag{15}$$

$$S_{on-line} = \delta.Ke + \dot{e} \Rightarrow S_{on-line}$$
$$= \{\left(A.e + \dot{e} + \frac{(A)^2}{2} \sum e\right) \times \left(A.e + \frac{(A)^2}{2} \sum e\right)\} M(q)(\ddot{q}_d + K_v \dot{e} + l$$

$$K_{Tune} = K.\delta \Rightarrow K_{Tune} = K\{\left(K.e + \dot{e} + \frac{(K)^2}{2}\sum e\right) \times \left(K.e + \frac{(K)^2}{2}\sum e\right)\}$$

Where (δ) is gain updating factor, $(\sum e)$ is the integral of error, $(\dot{e})$ is change of error, (e) is error and K is a coefficient.

4. RESULTS

This part is focused on compare between PD computed torque controller (CTC) and baseline error-based tuning computed torque controller (BCTC). These controllers were tested by step responses. In this simulation, to control position of PUMA robot manipulator the first, second, and third joints are moved from home to final position without and with external disturbance.

Tracking Performances: In baseline error-based tuning CTC the controller's gain is adjusted online depending on the last values of error (e), change of error $(\dot{e})$ and the integral of error $(\sum e)$ by gain updating factor (δ). Figure 3 shows tracking performance in BCTC and CTC without disturbance for step trajectory.

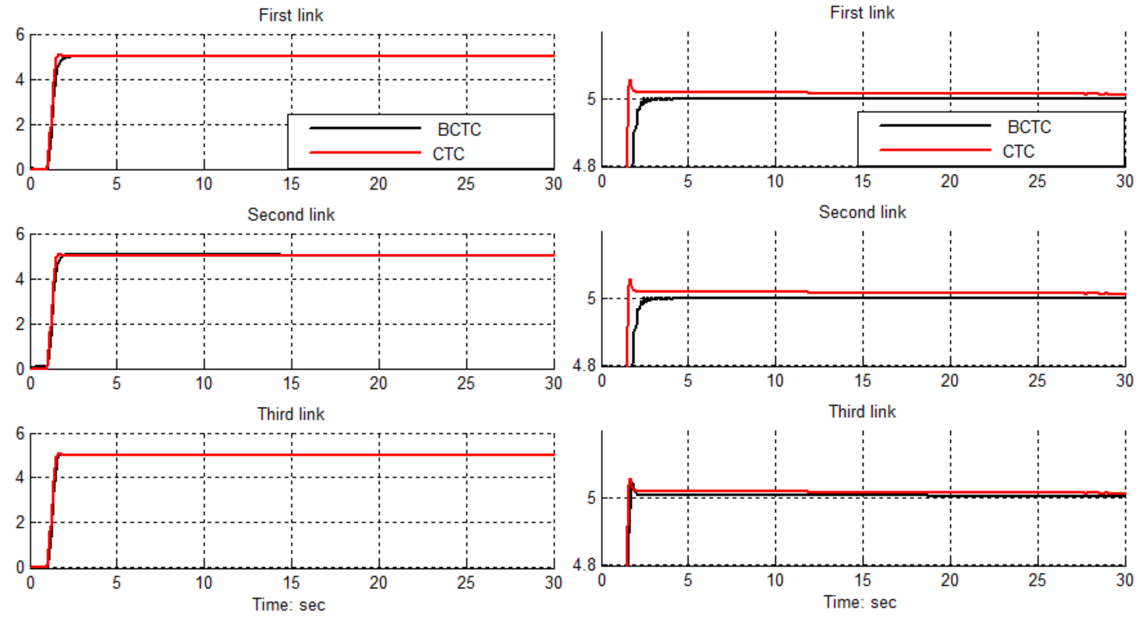

FIGURE 3: BCTC and CTC for first, second and third link step trajectory performance without disturbance

Based on Figure 3 it is observed that, the overshoot in BCTC is 0% and in CTC's is 7%, and the rise time in BCTC's is 0.5 seconds and in CTC's is 0.4 second.

Disturbance Rejection

Figure 4 shows the power disturbance elimination inn BCTC and CTC with disturbance for step trajectory. The disturbance rejection is used to test the robustness comparisons in these two controllers for step trajectory. A band limited white noise with predefined of 40% the power of input signal value is applied to the step trajectory.

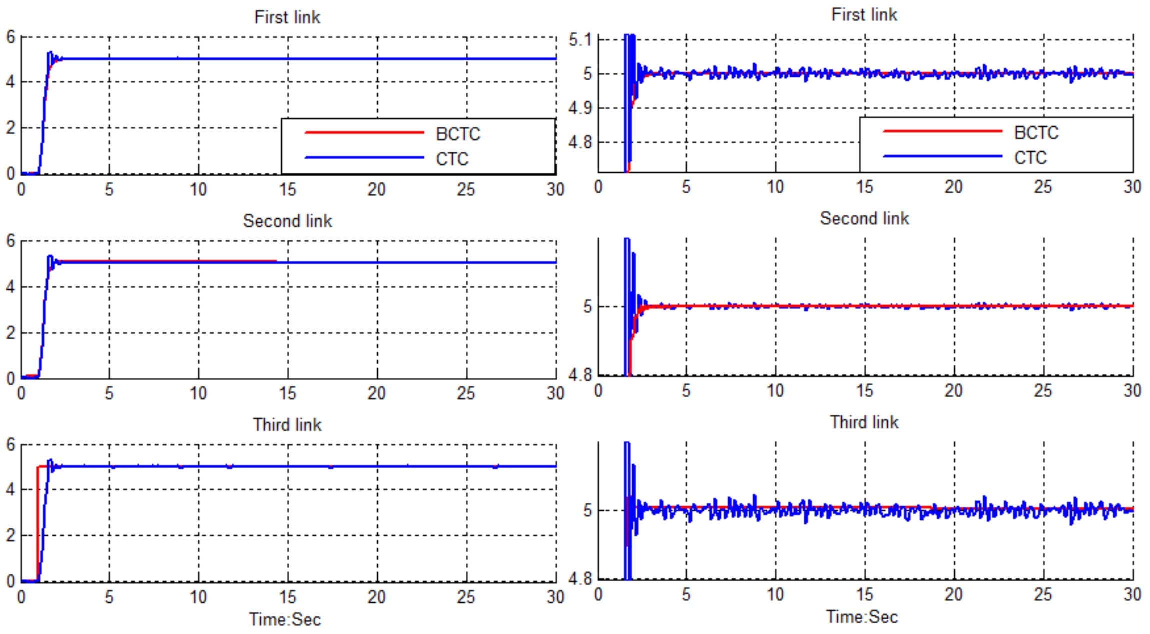

FIGURE 4: BCTC and CTC for first, second and third link trajectory with 40%external disturbance

Based on Figure 4; by comparing step response trajectory with 40% disturbance of relative to the input signal amplitude in BCTC and CTC, BCTC's overshoot about **(0%)** is lower than CTC's (**12%**). CTC's rise time **(1 seconds)** is lower than BCTC's **(1.4 second).** Besides the Steady State and RMS error in BCTC and CTC it is observed that, error performances in BCTC **(Steady State error =1.3e-5 and RMS error=1.8e-5)** are about lower than CTC's **(Steady State error=0.01 and RMS error=0.015).** Based on Figure 4, CTC has moderately oscillation in trajectory response with regard to 40% of the input signal amplitude disturbance but BCTC has stability in trajectory responses in presence of uncertainty and external disturbance. Based on Figure 4 in presence of 40% unstructured disturbance, BCTC's is more robust than CTC because BCTC can auto-tune the coefficient as the dynamic manipulator parameter's change and in presence of external disturbance whereas CTC cannot. The BCTC gives significant steady state error performance when compared to CTC. When applied 40% disturbances in BCTC the RMS error increased approximately 15.5% (percent of increase the BCTC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbanceRMS\ error} = \frac{1.8e-5}{1.16e-6} = 0.15\%$) and in CTC the RMS error increased approximately 125% (percent of increase the PD-SMC RMS error=$\frac{(40\%\ disturbance\ RMS\ error}{no\ disturbance\ RMS\ error} = \frac{0.015}{1.2e-6} = 125\%$).

5. CONCLUSION

In this research, a baseline error-based tuning computed torque controller (BCTC) is design and applied to robot manipulator. Pure CTC has difficulty in handling unstructured model uncertainties. It is possible to solve this problem by combining CTC and baseline error-based tuning. The controller gain is adjusted by baseline error-based tuning method. The gainupdating factor (δ) of baseline error-based tuning part can be changed with the changes in error, change of error and the integral (summation) of error. In pure CTC the controller gain is chosen by trial and error, which means pure CTC had to have a prior knowledge of the system uncertainty. If the knowledge is not available error performance is go up.

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