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Higher Performance Adaptive Control of a Flexible Joint Robot Manipulators

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Abstract: *Joint flexibility limits the performance of an industrial robot by introducing resonant frequencies in the same range of the control bandwidth. If joint flexibility is considered in the modelling, advanced control techniques can be designed to achieve a higher performance. This paper presents an adaptive control scheme for a two- degree of freedom flexible joint robot. The adaptive approach is applied to design a control signal for each joint (modeled by two- equations of second order), to withstand all uncertainties in parameters and load disturbances. Asymptotic stability is insured regardless of the joint flexibility value, by the use of Liapunov's direct method, i.e., the results are not restricted to weak joint elasticity. A simulation study was carried out to evaluate the performance of the proposed control law in case of flexible joint robot model. It was found that the adaptation technique is robust to parameters and load changes.*
Keywords: *Joint flexibility, model reference adaptive control, Tracking error, Liapunov's direct method, Dynamic interaction, Chatter, Adaptation signal*.

I. Introduction

Many control strategies have been proposed for the tracking control of robotic manipulators modelled by the rigid body dynamics of open kinematic chains [1,2]. This inherently nonlinear problem is further complicated by the changes in system parameters which occur when payloads are handled, leading to the development of controllers based on both model adaptation[3,4] and variable structure techniques[5-8]. However, the applicability of these controllers to practical robots is limited because the assumption of perfect rigidity is never satisfied exactly.

Sweet and Good [9, 10] have investigated the problem of robotic manipulation experimentally and identified several problems that limit the performance of a typical robot manipulator. One of the main issues is the unmodeled dynamics, especially the flexibility of the mechanical arm. For the particular manipulator tested, a resonance frequency of approximately 9 HZ was observed due to joint torsional flexibility. Rivin [11] studied several robot manipulators and determined many sources of flexibility such as harmonic drives, the presence of elastic drive belts and the compressibility of hydraulic fluid in hydraulic manipulators. The presence of this flexibility in the drive system leads to lightly damped oscillations in the open –loop response and the use of "rigid" control laws in such systems has been shown to result in poor tracking performance with a low controller bandwidth and instability at higher bandwidth [12].

Several control strategies [13-15] have been proposed for the control of manipulators with joint flexibility based on reduced-order system models derived in separate time-scales using singular perturbation techniques. However, the problems associated with parameter variations have not been addressed in these works. Therefore, consideration of the joint flexibility in the course of modelling and control can contribute significantly to a better performance for most industrial robots.

Robust tracking controller for **(FJR)** is developed using voltage control strategy [16], achieving pre-set performance on link position error [17] both are free of manipulator dynamics and nonlinearities. Adaptive trajectory control scheme consists of a direct (MRAS) is presented [18] to improve damping of vibration at the joints. An adaptive fussy output feedback approach is proposed [19] to compensate for nonlinear dynamics while only requiring the measurement of link position.

This paper investigates the position control of a two-degree of freedom flexible joint robot (FJR) manipulator. A model reference adaptive control (MRAC) algorithm is introduced. An adaptive signal is applied to the robot model additionally to conventional control signal. The proof of the stability of the proposed control is carried out by the use ofLiapunov's direct method. The adaptation criterion is the asymptotic stability of the generalized error vector. Finally comparativesimulation is presented to evaluate the performance of the (MRAC) algorithm for position control of (FJR) under parameter uncertainty and payload variations.

Dynamic Model for (Fjr)

This section describes the dynamic model of the robot. This model is used for the design and control development. The dynamic model for flexible joint robot developed by Spong [20] is adopted. It is derived for the experimental robot using Euler-Lagrange equation [21], and it is given by the following equations:

$D(q)\ddot{q} + C(q,\dot{q}) + B\dot{q} - K(q_m - q) = -J^T F$ (1)

$I_m\ddot{q}_m + B_m\dot{q}_m + K(q_m - q) = U$ (2)

Where q is the 2 x 1 link angular position vector, q_m is the 2 x 1 motor angular position vector, D (q) is the 2x2 manipulator inertia matrix, C (q,$\dot{q}$)is the 2x1 coriolos and centrifugal forces vector, K is 2x2 diagonal matrix with entries equal to the joint stiffness, J^T is the 2x2 transpose of the manipulator Jacobian, F is 2x1 forces vector at the end effector expressed in the reference frame, I_m is the 2x2 diagonal matrix with entries equal to the rotors inertia, B_m is the 2x2 diagonal matrix with entries equal to the coefficient of viscous damping at the motors, and U is 2x1 applied motor torque vector. The inertia matrix and the coriolos and centrifugal forces vector are given by:

$$D(q) = \begin{bmatrix} d_1 + 2d_2\cos(q_2) & d_3 + d_2\cos(q_2) \\ d_3 + d_2\cos(q_2) & d_3 \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} -\dot{q}_2(2\dot{q}_1 + \dot{q}_2)\sin(q_2) \\ \dot{q}_2^2 d_2\sin(q_2) \end{bmatrix}$$

Where

$d_1 = I_1 + I_2 + a_1^2 m_1 + l_1^2 m_{r2} + m_2(l_1^2 + a_2^2)$

$d_2 = 2\, m_2 l_1 a_2$

$d_3 = l_2 + a_2^2 m_2$

Where I_1 , I_2 , m_1 , m_2 , a_1 , a_2 , l_1 , l_2 , and m_{r2} are the moment of inertia about an axis parallel to the axis of rotation passing through the center of mass, the mass, the distance from the center of rotation to the center of mass, length of the first and second link, respectively, and the mass of the second rotor. The system undamped natural frequencies are given by the following characteristic equation:

$$\left|\begin{bmatrix} K & -K \\ -K & K \end{bmatrix} - \omega^2 \begin{bmatrix} D(q) & 0 \\ 0 & I_m \end{bmatrix}\right| = 0 \quad (3)$$

The system has four natural frequencies. The first two correspond to the rigid body modes which are the free rotation of the two rotors. The remaining two natural frequencies are due to joint flexibility and are used in the design of the flexible joints.

II. Problem Formulation

The process of controlling the dynamic model given by equations (1) and (2) is difficult because the system is multi-input multi-output (MIMO) nonlinear. However, considering each link and its driving motor only reduces the system to two single input multi-output linear subsystems, whichsimplifies the identification and control process. [22] Has implemented this identification technique on a two-link flexible joint experimental robot Fig. 1.The first subsystem is the first joint (the first motor and the first link) and the second subsystem is the second joint (the second motor and the second link). The following procedures are performed to control these two subsystems.

a) First, constrain the first subsystem by clamping the first link to the fixed table, and thus the second subsystem characteristic can be isolated, identified, and control.
b) To identify and control the first subsystem, the brake of the second motor is applied. Hence, the second subsystem is considered as extra mass add to the end of the first link.

The following state space model represents any of the two subsystems discussed above.

$$\begin{bmatrix} \dot{q}_m \\ \ddot{q}_m \\ \dot{q} \\ \ddot{q} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -k/j_m & -b_m/j_m & k/j_m & 0 \\ 0 & 0 & 0 & 1 \\ k/j_l & 0 & -k/j_l & b_l/j_l \end{bmatrix} \begin{bmatrix} q_m \\ \dot{q}_m \\ q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ 1/j_m \\ 0 \\ 0 \end{bmatrix} u \quad (4)$$

Where q_m, q are the motor and the link angular position respectively, k is the joint torsional stiffness, j_m and j_l are the effective inertias of the rotor and the link, respectively. U, is the applied motor torque which is proportional to the desired position at time equal zero.

Equation (4) is used to represent the robot axis dynamics for each joint, taking into account the load variation disturbance F(t), and using conventional controller with tuning parameters k_p and k_t as shown in Fig. 2. From this diagram one can drive the following:

$(s^3 + a\,s^2 + b\,s + k)\,\dot{q}_s(s) = k q_d(s) + k\,(g(s) - F(s))$ (5)

Where

$$a = \frac{b_m j_l + b_l j_m}{j_m j_l}$$
$$b = \frac{b_m b_l + j_l k + j_m k}{j_m j_l} \quad (6)$$
$$k = \frac{k_p k_t k\,(b_l + b_m)}{j_m j_l}$$

For the system of equations (5, 6) one can increase the response time if higher gain $k_t$is applied. Also, it is possible that by tuning the value of k_t and k_p a good transient response of the overall system can be achieve. All these can be done only on the base of the previous knowledge of all parameters in Eqn. (5,6). Due to existence of disturbance force F(t) there is a steady state error in position. To overcome this one can introduce a feed forward signal g(t), for computing g(t) it is need to know F(t) and its derivative which is difficult because its variation is not always known in advance.

It is very reasonable to apply an adaptive control signal g(t) to withstand all uncertainties and disturbance effects. In robot control the position and velocity of each joint can usually be precisely measured. Thus all the state variable of the joint dynamics are reachable. Thus, Model Reference Adaptive Control (MRAC) approachis applied to position control of the flexible joint robot (FJR).

Design Of Adaptation Signal For (Fjr)

We introduce a stable reference model of the form

$$(s^3 + a_m s^2 + b_m s + k_m)\ q_m(s) = k_m q_d(s) \quad (7)$$

Without the information about the parameters k, a, b and disturbance F we intend to find such an adaptation signal g(t) that the movement of the robot joint $q_s(t)$ follows $q_m(t)$ as closely as possible.

By defining error in the following form:

$$x_1(t) = q_m(t) - q_s(t) \quad (8a)$$
$$x_2(t) = \dot{q}_m(t) - \dot{q}_s(t) \quad (8b)$$
$$x_3(t) = \ddot{q}_m(t) - \ddot{q}_s(t) \quad (8c)$$
$$X = [[x_1, x_2, x_3]^T \quad (8d)$$
$$e(t) = q_d(t) - q_s(t) \quad (8e)$$

The following equation can be obtained using Eqn.[5, 7, 8]

$$(s^3 + a_m s^2 + b_m s + k_m)\ x_1(s) = (k_m - k)\ e(s) + (a - a_m)\ddot{q}_s(s) + (b - b_m)\dot{q}_s(s) + k(F(s) - g(s)) \quad (9)$$

Eqn. (9) is named as the error dynamics and intend to find such adaptation signal g(t) which would make this error dynamics asymptotically stable. In this case, the model matching is achieved. The signal g(t) is to be found in the following form.

$$g(t) = g_1(t)e(t) + g_2(t)\dot{q}_s(t) + g_3(t) + g_4(t)\ddot{q}_s(t) \quad (10)$$

The state space equation of the error dynamics Eqn.(9) is :

$$\dot{x}(t) = A_m\, x(t) + b_1\, e(t) + b_2\dot{q}_s(t) + b_3 + b_4\ddot{q}_s(t) \quad (11)$$

Where

$$A_m = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -k_m & -b_m & -a_m \end{bmatrix}; \quad b_1 = \begin{bmatrix} 0 \\ 0 \\ k_m - k - kg_1(t) \end{bmatrix}; \quad b_2 = \begin{bmatrix} 0 \\ 0 \\ b - b_m - kg_2(t) \end{bmatrix}$$

$$b_3 = \begin{bmatrix} 0 \\ 0 \\ k(w - g_3(t)) \end{bmatrix}; \quad b_4 = \begin{bmatrix} 0 \\ 0 \\ a - a_m - kg_4(t) \end{bmatrix} \quad (12)$$

If Eqn. (11) is asymptotically stable then our goal is attained. Thus we have to find an adaptation law for $g_i(t)$ i= 1 to 4 that the dynamic Eqn. (9) will be asymptotically stable.

By choosing the Liapunov function as:

$$V = x^T P x + \sum_{i=1}^{4} \alpha_i b_i^T b_i \quad (13)$$

Where $P = P^T > 0$ and $\alpha_i > 0$; for i = 1,2,3,4.

Its derivation with respect to time is:

$$\dot{V} = x^T Q x + 2\sum_{i=1}^{4} \alpha_i\, b_i^T b_i + 2x^T P b_1 e(t) + 2x^T P b_2 \dot{q}_s(t) + 2x^T P b_3 + 2x^T P b_4 \ddot{q}_s(t) \quad (14)$$

If we choose

$$\dot{b}_1^T = -\frac{1}{\alpha_1} x^T P\, e(t) \quad (15a)$$
$$\dot{b}_2^T = -\frac{1}{\alpha_2} x^T P \dot{q}_s(t) \quad (15b)$$
$$\dot{b}_3^T = -\frac{1}{\alpha_3} x^T P \quad (15c)$$

$\dot{b}_4^T = -\frac{1}{\alpha_4} x^T P \ddot{q}_s(t)$ (15d)

and

$P A_m + A_m^T P = -Q \; ; \quad Q = Q^T > 0$ (16)

$\dot{V} = x^T Q x \; < 0 \, for \, all \; x \neq 0$ (17)

With the assumption that the joint's parameters and disturbance forces are slowly variable one can use the following algorithms:

$\dot{g}_1(t) = \gamma_1 x^T P_3 \, e(t)$ (18a)

$\dot{g}_2(t) = \gamma_2 x^T P_3 \dot{q}_s(t)$ (18b)

$\dot{g}_3(t) = \gamma_3 x^T P_3$ (18c)

$\dot{g}_4(t) = \gamma_4 x^T P_3 \ddot{q}_s(t)$ (18d)

Where $\gamma_i > 0$ (I = 1,2,3,4) ; P_3 denotes the third column of matrix P.

One can deduce from Eqn. (13) to Eqn. (18) that the error dynamics of Eqn. (11) is globally stable.

The steps of the proposed method

1) Choose the reference model according to Eqn.(11). This means setting the value a_m, b_m, k_m.
2) Choose γ_i I = 1,2,3,4> 0.
3) Choose the Q matrix to be positive definite symmetric and solve the Liapunov equation for Q if we choose Q = diag {λ_i I = 1,..,4}, the solution of Eqn. (16) is

$$\mathbf{P_3} = \begin{bmatrix} \frac{\lambda_1}{2k_m} \\ \frac{a_m}{2(a_m b_m - k_m)} \left(\frac{a_m \lambda_1}{k_m} + \lambda_2 + b_m \lambda_3 \right) - \frac{\lambda_3}{2} \\ \frac{1}{2(a_m b_m - k_m)} \left(\frac{a_m \lambda_1}{k_m} + \lambda_2 + b_m \lambda_3 \right) \end{bmatrix} \quad \mathbf{(19)}$$

4) Compute the error vector x as given in Eqn. (8) by using the measured values of $q_s(t), \dot{q}_s(t)$ computing the derivation of $\dot{q}_s(t) to \; get \; \ddot{q}_s(t) and$ the precomputed values of $q_m(t), \dot{q}_m(t), \ddot{q}_m(t)$. Also compute e(t) according to Eqn. (8e).
5) Compute the adaptation signal g(t) according to Eqn. (18) and (10) by an appropriate choice of γ_ii = 1,..,4. The block diagram of the overall adaptive control system is shown in Fig. 2.

III. Simulation Study

To evaluate the performance of the proposed model reference adaptive controller developed for position control of a two-degree of freedom flexible joint robot (FJR) manipulator, a series ofsimulation studies was carried out.Simulation program for each joint prepared using VisSim language. The obtained results were compared with those of conventional controller whose gain is constant. Eqn. (5) and (6) were used for the mathematical model of the robot joint systems. Ofcourse we do not need to know exactly the total robot joint dynamic model but the system parameters used in the simulation study are chosen as listed in table 1.[22].

Table 1. Robot parameter from design and Sin Sweep Identification

	J_{l1} (Kg.m^2)	J_{l2} (Kg.m^2)	d_1 (Kg.m^2)	d_2 (Kg.m^2)	b_1 (N.m.s/rad)	b_2 (N.m.s/rad)
Sin Sweep			**2.087**	**0.216**	**2.041**	**0.242**
I - DEAS	**0.2269**	**0.0429**	**2.110**	**0.223**		

	b_{m1} (N.m.s/rad)	b_{m2} (N.m.s/rad)	k_1 (N.m/rad)	k_2 (N.m/rad)	J_{m1} (Kg.m^2)	J_{m2} (Kg.m^2)
Sin Sweep	**1.254**	**0.119**	**125.56**	**31.27**	**0.1224**	**0.0168**
I - DEAS			**198.49**	**51.11**	**0.1226**	**0.017**

Evaluation of the control methodology was carried out for:

a) Different external load disturbance, as shown in Fig. 3a and Fig. 3b.
b) Various controller parameters [λ_i ,γ_i].

The reference model is selected to be: ($S^3 + 32 S^2 + 340 S + 1200$) $q_m(t) = 1200 \; q_d(t)$

To study the effect of the controller parameters, different values of γ_ii = 1,..,4 were selected and they are listed in Table 2. Also, component of P matrix [P_{31}, P_{32}, P_{33}] were varied by varying the Q matrix. In this case P_3 and Q matrix were selected so as to satisfy the inequality conditions Eqn. (13) to Eqn. (19).

Table 2. Controller parameter values for computer simulation (λ_i , P_3 ,and γ_i)

case	γ_i	λ_i	P_3
1	$[100,100,100,100]^T$	$[150,150,150,150]^T$	$[0.063,9.55,2.643]^T$
2	$[100,100,100,100]^T$	$[100,100,100,100]^T$	$[0.042,6.368,1.762]^T$
3	$[100,100,100,100]^T$	$[60,60,60,60]^T$	$[0.025,3.821,1.057]^T$
4	$[75,75,75,75]^T$	$[100,100,100,100]^T$	$[0.042,6.368,1.762]^T$
5	$[50,50,50,50]^T$	$[100,100,100,100]^T$	$[0.042,6.368,1.762]^T$

The value of $K_p = 0.68$, $K_t = 0.0101$ for first joint, and $K_t = 0.0015$ for the second joint were chosen.

IV. Results And Discussion

A number of simulations have been carried out to evaluate the performance of the proposed control strategy. The obtained results of the simulation,(the robot position responses of the (MRAC) and also, those of the conventional constant feedback controller) are plotted for a comparison purpose.

Effects of controller parameters [λ_i , γ_i]

Effects of (λ_i). To study the effect of (λ_i) on the performance of the proposed control strategy, different values of the third column of the matrix $\mathbf{P_3}$ were determined and varied while keeping the other controller parameters (γ_i) at a constant value. Utilizing these values as given in Table 2; the robot position responses of the (MRAC) were obtained for the case of the load disturbance given in Fig. 3b. Fig. 4 and Fig. 5 show the position responses for controller parameters cases 1 and 3 respectively. One can see that increasing [(λ_i) or P_3] to an optimum value, the robot position response is almost identical to the model reference. It can be concluded that the value of (λ_i) has a significance effect on the robot response.

Effects of (γ_i). As shown in Eqn.'s (18a) & (18b) the (γ_i's) behave as a weighting factor of the position error, velocity and acceleration. To investigate the effect of this controller parameter their values were varied while keeping the other parameters (λ_i) at a constant value. Refer to values given in Table 2, the robot position response of the (MRAC) were obtained for the case of load disturbance given in Fig. 3b. Fig. 6 and Fig. 7 show the robot position response for cases 2 and 5 respectively. It is easy to see that the robot position response of the proposed (MRAC) system using the optimum value of (γ_i) is almost identical to the model reference response. So, in view of these cases both of the controller parameters have a significant effect and must be carefully selected in consideration of each problem.

Effects of load disturbance

Let the variation of load disturbance be considered as shown in Fig. 3a and Fig. 3b. Fig. 8 and Fig. 9 show the robot position responses for the two previous load disturbances respectively, and for controller parameters defined in Table 2 case 4. As can see from these figures, changing the load disturbance from sinusoid to a series of severe step changes leads to increase the steady state error in both the conventional and (MRAC) responses. Fig. 10 shows the robot response for controller parameters case 1, and step disturbance case. Comparing with response in Fig. 9, one can see that optimum controller parameters case 1 decrease the steady state error for the same disturbance. Based upon the obtained results, it can be concluded that the proposed control strategy for the presented (FJR) model is robust to various uncertainties and load variations in comparison to conventional controller.

V. Conclusion

The problem of tracking control of a two-link direct drive robot with flexible joints (FJR) is considered, in the presence of disturbances and parameters uncertainties. Each joint is represented by two second order equations. It was found that joint stiffness can be used alone as the design criterion to allocate the resonant frequencies as desired. The response characteristics were investigated for different controller parameters and load disturbances. The results were compared with those of conventional constant gain controller. It seems that, the position response follows exactly that of the desired model, in spite ofthe existing disturbances. Also, it was found that the controller parameters (γ_i ,λ_i) have a significant effect on the robot response (tuning parameters). The results assure that the presented flexible joint model support to design an advanced control technique to achieve a higher control performance.

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Fig. 1 Solid model of the used robot

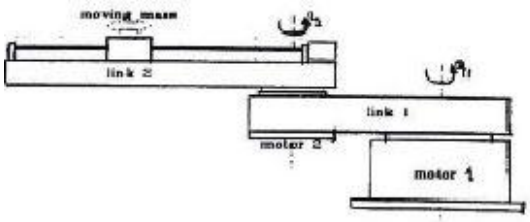


Fig. 2 The proposed control scheme of (FRJ) modeld by two second order equations.

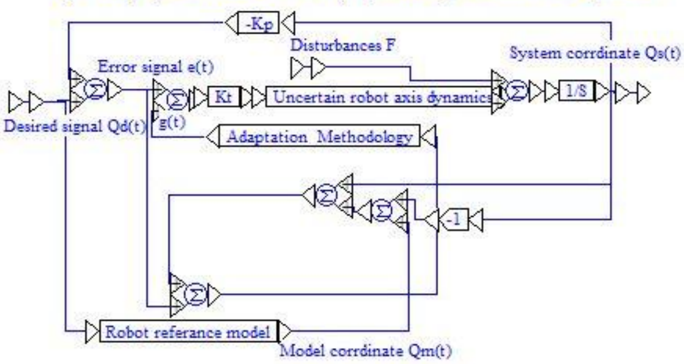


Fig. 3a Variation of load disturbance
Step signal

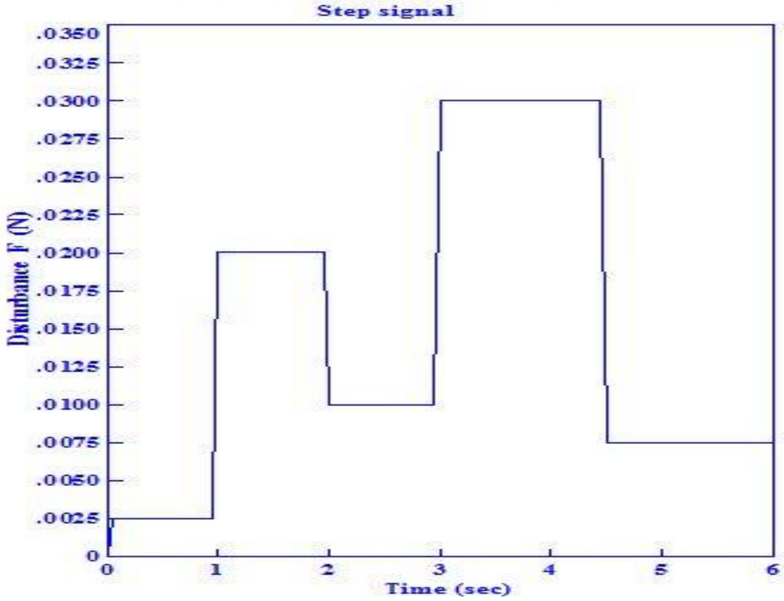


Fig. 3b Variation of load disturbance
Sinsoud signal

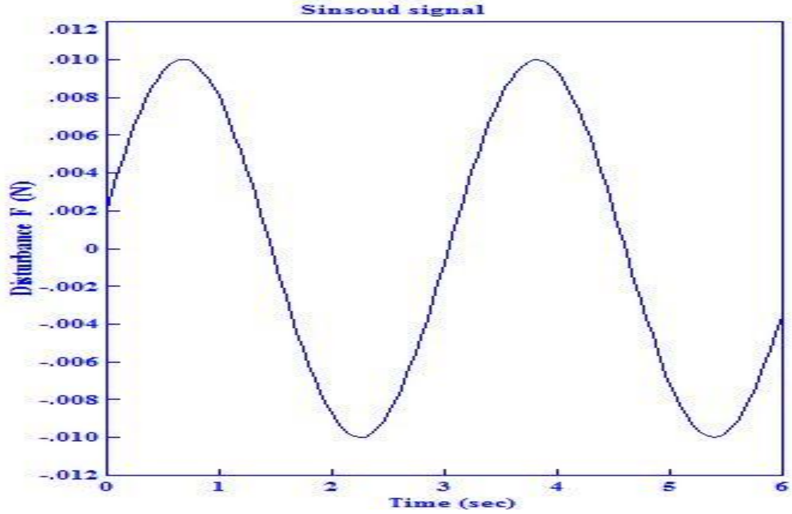


Fig. 4a Robot position response for joint (1)
Controller parameters case (1),

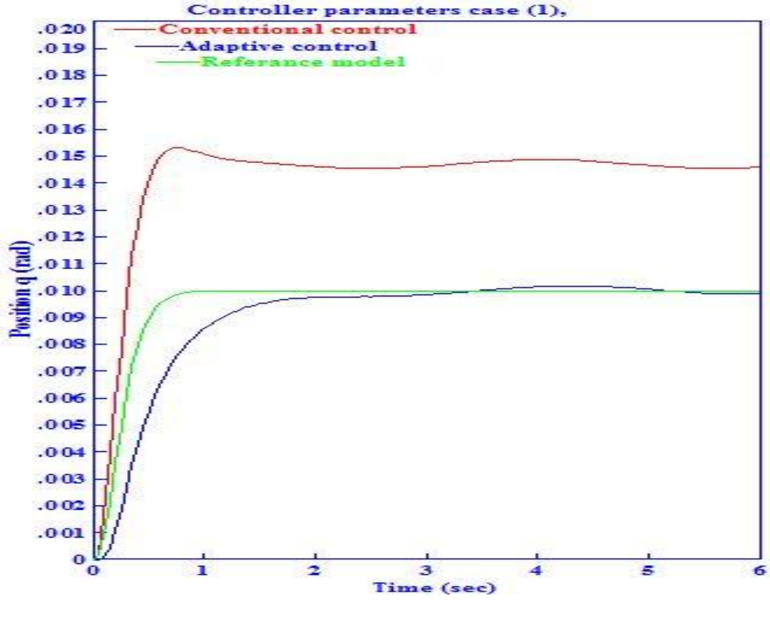


Fig. 4b Robot position response for joint (2)
Controller parameters case (1)

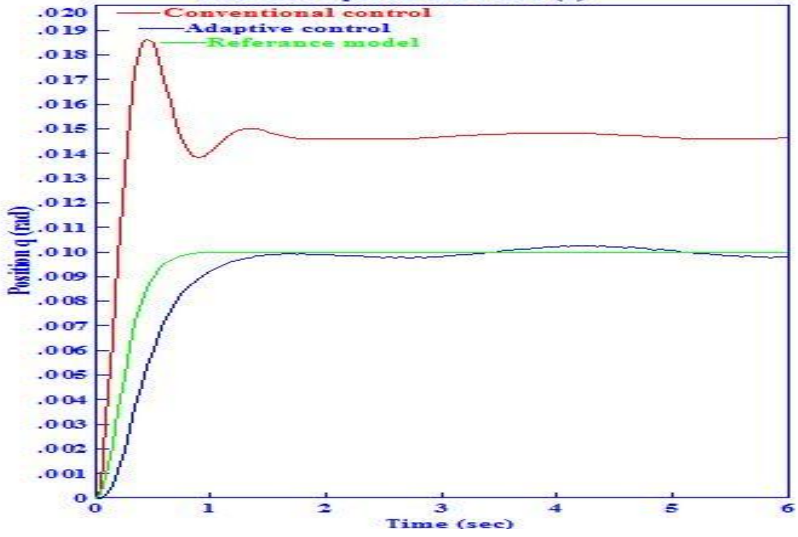


Fig. 5a Robot position response for joint (1)
Controller parameters case (3),

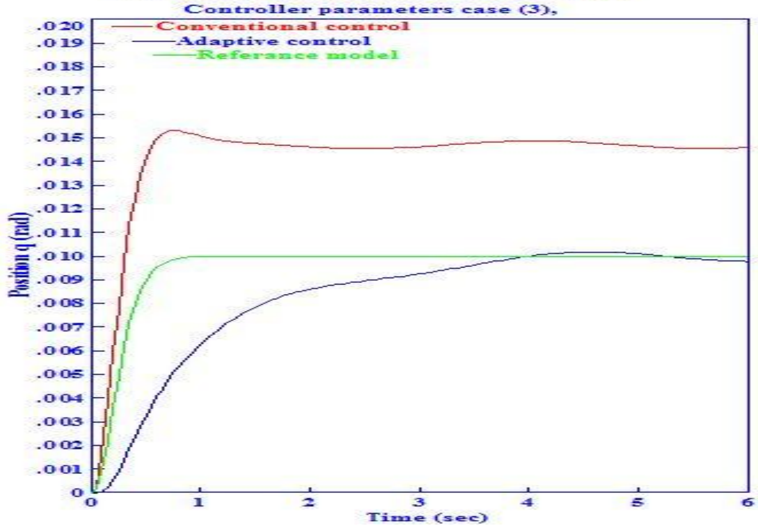


Fig. 5b Robot position response for joint (2)
Controller parameters case (3)

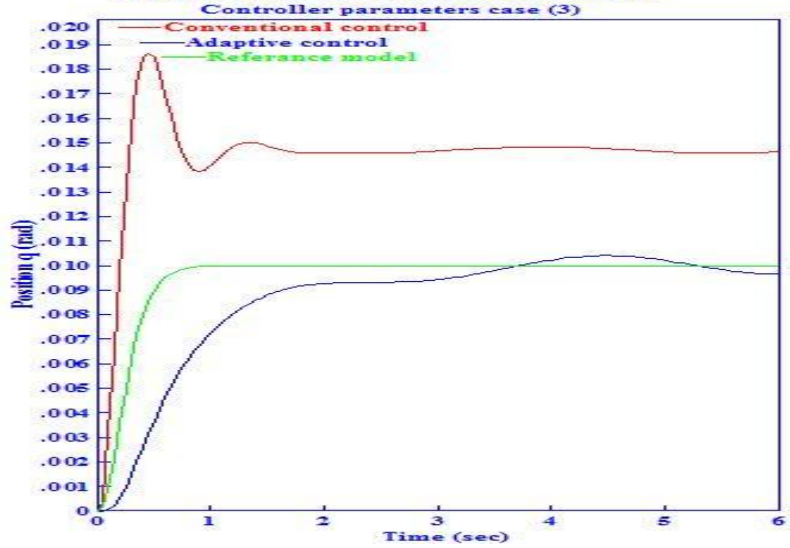


Fig. 6a Robot position response for joint (1)
Controller parameters case (2),

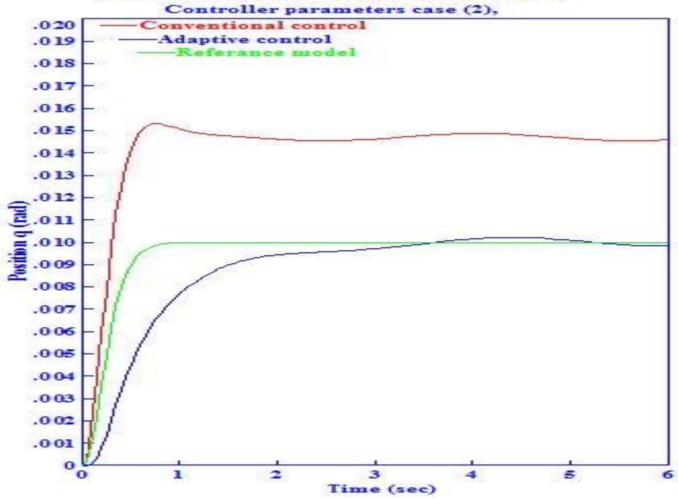


Fig. 6b Robot position response for joint (2)
Controller parameters case (2)

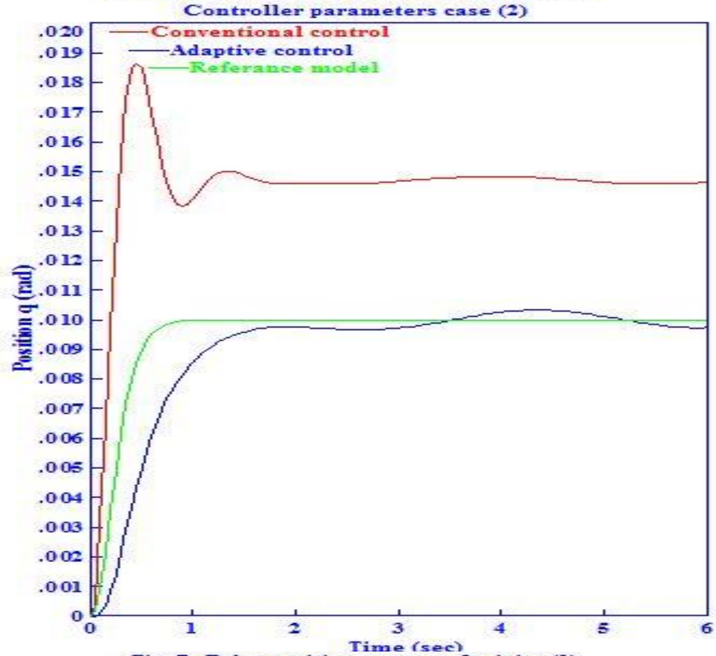


Fig. 7a Robot position response for joint (1)
Controller parameters case (5)

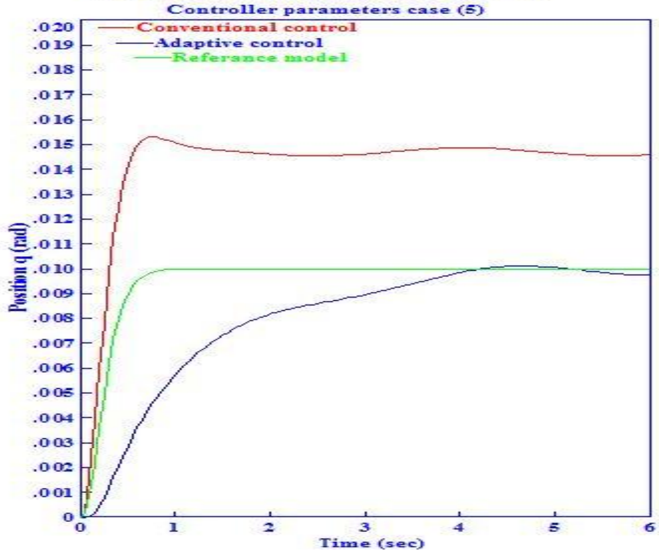


Fig. 7b Robot position response for joint (2)
Controller parameters case (5)

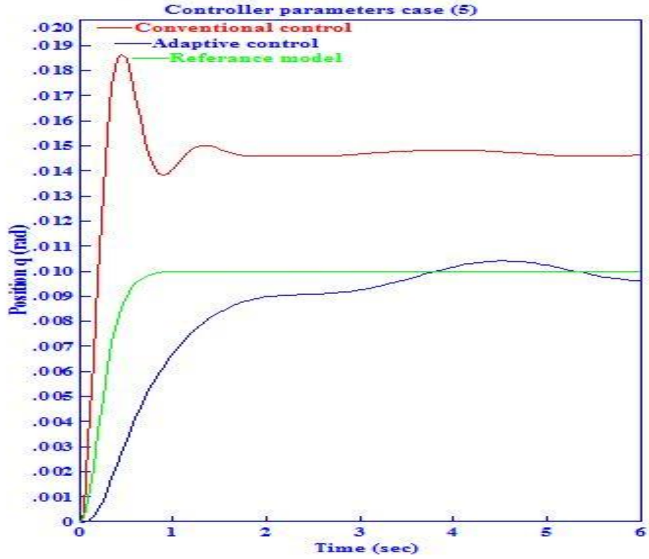


Fig. 8a Robot position response for joint (1)
Controller parameters case (4), sinusoid load

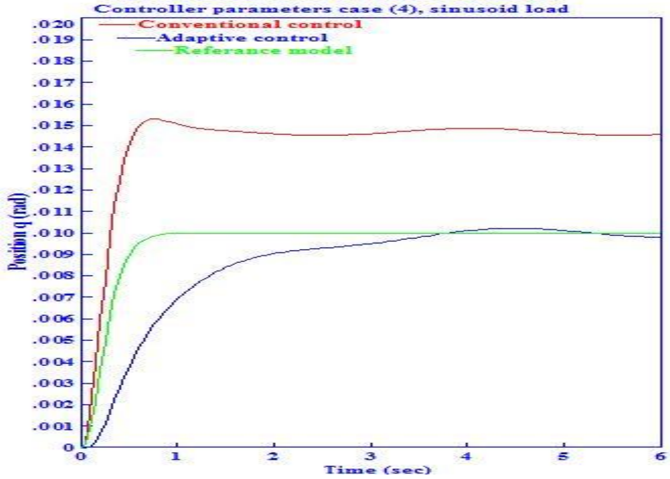
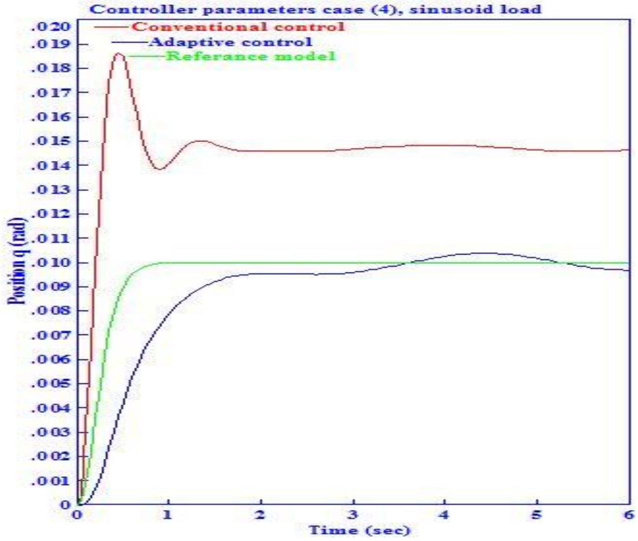


Fig. 8b Robot position response for joint (2)
Controller parameters case (4), sinusoid load



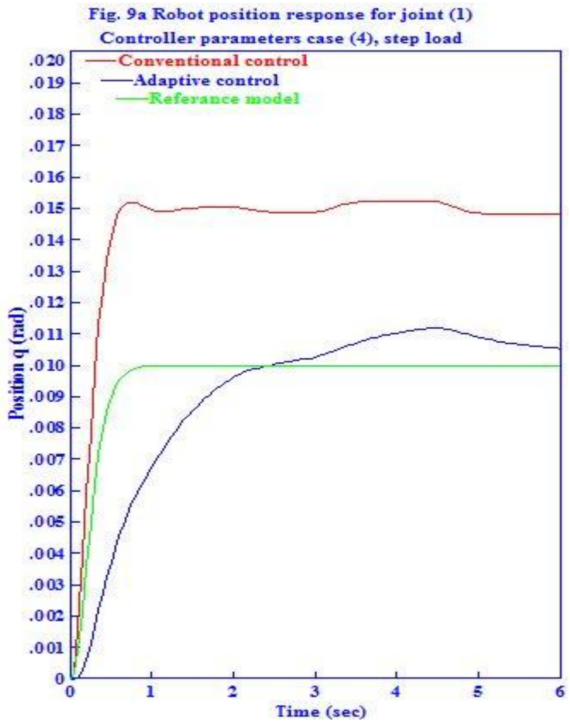


Fig. 9a Robot position response for joint (1)
Controller parameters case (4), step load
Conventional control
Adaptive control
Referance model
Position q (rad)
Time (sec)
.020
.019
.018
.017
.016
.015
.014
.013
.012
.011
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
0
1
2
3
4
5
6

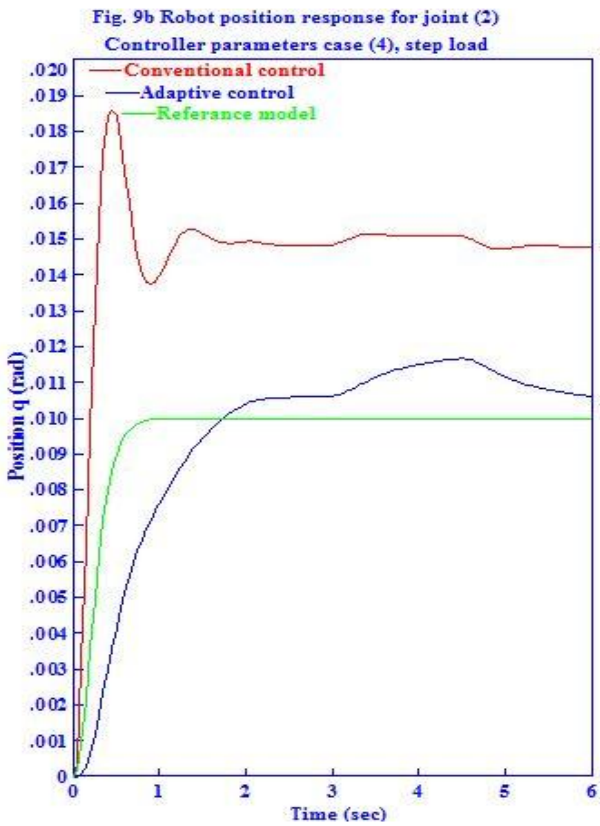


Fig. 9b Robot position response for joint (2)
Controller parameters case (4), step load
Conventional control
Adaptive control
Referance model
Position q (rad)
Time (sec)
.020
.019
.018
.017
.016
.015
.014
.013
.012
.011
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
0
1
2
3
4
5
6

Fig. 10a Robot position response for joint (1)
Controller parameters case (1), step load

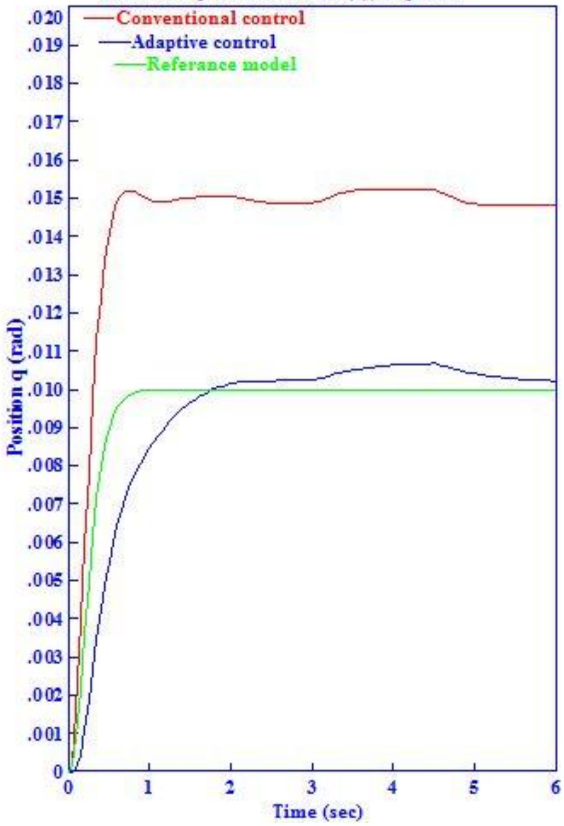


Fig. 10b Robot position response for joint (2)
Controller parameters case (1), step load