Advantages of application of non-linear MPC to 2-DOF direct driven industrial robot manipulator

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Abstract:

Applications of the Model Based Predictive Control technique (MPC) to the different fields of industry found a great success. However, application of MPC to robot manipulators still limited, because of their fast Non-linear dynamics and probably, due to policy of manufacturers. This paper is one of series of papers studying the application of non-linear MPC strategy to an industrial robot manipulator of two degrees of

freedom (2-DOF). The study sustains advantages of MPC strategy and includes comparison with the most used conventional control technique. The robot manipulator under investigation is direct driven (DDA) which means has a non-linear model and high joint coupling.

Introduction:

Generally, the used control strategy has a significant impact on the performance of the robot manipulators. Whereas the mechanical design, has an influence on the required type of the control strategy. Also, the technological improvements in robot manipulators manufacturing and the appearance of powerful computers make possible applications of advanced control schemes. Most of the manipulators, which are in use, are considered as MEMO (Multi-Input Multi-Output), however, they applying conventional SISO (Single-Input Single-Output) control systems like PI, PD, PID, or probably, CTC-PD controller. Moreover, robot manipulators are characterized by their non-linearity. However, application of gears drastically reduces the non-linearity [1, 2]. During the last decades, an intensive study was devoted to the application of the promised control technique family known by Model-Based Predictive Control technology (MPC) [3, 4]. The linear MPC proofs its capability to governing the motion of industrial manipulator [5, 6]. A very encouragement results have been achieved from success applications of MPC, particularly in petroleum and chemical industries [7]. What distinguishes MPC technique among the other techniques, are its explicit use of the process model and involving plant output constraints [3, 4]. This feature provides high degree of economy and safety. Applying non-linear control techniques for sure leads to more sophisticated results. An experimental study proves precise trajectory tracking and robustness in controlling of speed of Permanent Magnet Synchronous Motor PMSM (considered as one DOF), works under Improved MPC [8]. There are many different applicable MPC control strategies. In this paper the MPC-Nonlinear with Successive Linearization (MPC-NSL) strategy will be used. This strategy is based on a successive linearization of the manipulator's model, about the calculated position [4]. Taylor's expansion series method is applied as a linearization technique [10]. Furthermore, the joint angle positions are part of the state space variable vector and the disturbances and modeling errors are taken in consideration [4]. The simulation results show the superiority achieved by MPC to the conventional control system, further, ISE criterion [11], used to sustain this result.

MPC strategy;

The philosophy of operation of the predictive control algorithm is based on that, at each sampling instant calculating of the optimum input through minimizing a cost function (performance index). The first calculated sequence is applied to the plant over a control horizon N_u. At the next sampling instant, the calculation process is repeated over the prediction horizon N_p where $N_p \geq N_u$ and N_p might be infinite.

Robot manipulator's Dynamic model and parameter values

The general form of the manipulator forward dynamic equation (1), in joint space form, is driven from Euler-Lagrangian equation:

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

where; $q, \dot{q}$ *and* $\ddot{q}$ are n x 1 vectors of the joint angle, joint velocity and joint acceleration respectively, in which n is the number of joints (also equal to DOF), τ is the n x 1 actuator's applied torque vector; $M(q)$ is n x n positive definite symmetric inertia matrix; $N(q,\dot{q})$ is the Coriolis and Centrifugal torque vector, $F(q,\dot{q})$ is the linear and non-linear friction torque vector and $G(q)$ is the gravity torque vector [3].

The dynamic model of the 2-DOF robot manipulator figure (1) is given by the general compact form equation (2), [12]:

$$\left.\begin{aligned} &The\,inertia\,matrix; M(q) = \begin{bmatrix} p_1 + 2p_3\cos(q_2) & p_2 + p_3\cos(q_2) \\ p_2 + p_3\cos(q_2) & p_2 \end{bmatrix} \\ &The\,cent.and\,coril\,matrix; N(q,\dot{q}) = \begin{bmatrix} -p_3\sin(q_2)\dot{q}_2 & -p_3\sin(q_2)(\dot{q}_1+\dot{q}_2 \\ p_3\sin(q_2)\dot{q}_1 & 0 \end{bmatrix} \\ &The\ friction\,term; F(q,\dot{q}) = \begin{bmatrix} f_{d1} & 0 \\ 0 & f_{d2} \end{bmatrix}\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} f_{s1} & 0 \\ 0 & f_{s2} \end{bmatrix}\begin{bmatrix} \mathrm{sgn}(\dot{q}_1) \\ sign(\dot{q}_2) \end{bmatrix} \end{aligned}\right\} \quad (2)$$

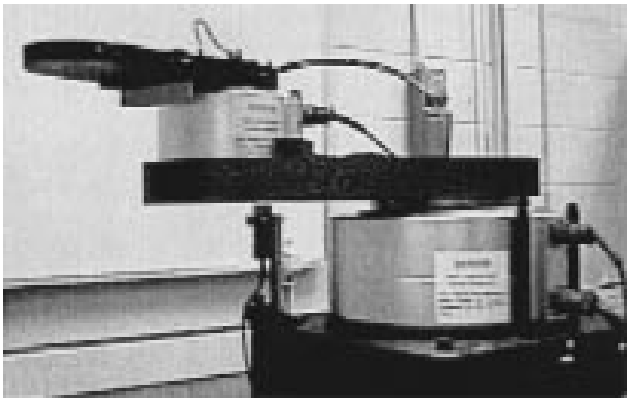

Figure: 1 the 2-DOF robot

The nominal values of the manipulator parameters are (the inertial parameters have been regrouped into parameters p_1, p_2 *and* p_3 and the mass distribution is not given):

$p_1 = 3.473\ kgm^2$; $p_2 = 0.193\ kgm^2$ and $p_3 = 0.242\ kgm^2$ whereas the friction constants as: $f_{d1} = 1.3\ \tilde{l}$, $f_{d2} = 0.88\ N$; $f_{s1} = 1.519\ Nm/s$, and $f_{s2} = 0.932\ Nm/s$.

Notice that the gravity vector $G(q)$ equals to zero (robot has horizontal motion only).

Desired trajectories:

Industrial manipulator tasks are either pick and place (e g material handling) or following a smooth trajectory (e g painting). In general, two types of joint trajectories are suggested. The sinusoidal waveform represents a continuous and smooth trajectory whether step function represents abrupt change mimic the motion of the industrial robot. In this study we will apply a unit step. Accordingly; the joint desired trajectories take the form (3):

$$q_i^d(t) = \begin{cases} 1\ \forall t > 0, i = 1, 2 \\ 0\ \forall t < 0, i = 1, 2 \end{cases}, \textit{ where } q_i^d \textit{ is the desired trajectory of the } i \textit{ join.t} \qquad (3)$$

Control Algorithm:

For the purpose of study, performance of the Model-Based Predictive Non-linear Control technique is compared with the performance of the most known and widely applied to manipulators, PI-controller.

PI-control technique

The general form of the control law is (4):

$$\tau_j = K_{jp}(e_j(k) + K_{ji}\int e_j(k)) \qquad (4)$$

Where; τ_j is the torque of the joint *j* and $e_j(k) = q_j^d(k) - q_j(k)$ is the joint *j* angle position error, $q_j^d(k)$ is the joint *j* desired (reference) angle position at the instant *k*, whereas K_{jP}, *and* K_{ji} are the proportional gain, and reciprocal of integral time respectively. Nichols method has been used to get ultimate values of the controller parameters. Moreover, the system may further tune using try and error rule. From the technical specifications, the minimum and maximum allowable input torque forces are (5):

$$\tau_{\min/\max} = -[225.4,\ 36.2]/+[225.4,\ 36.2]Nm \ [12]. \qquad (5)$$

MPC algorithm:

Applying a non-linear cost function is quite possible, but it leads to high computational burden (time consuming). As a solution to this problem, MPC-NSL approach is proposed as practical alternative. Taylor's series expansion method about the current joint's position and velocity is used. The current joint's position and velocity are calculated from applying the state-space model. In this algorithm the used model is the model resulting from the linearization process of the manipulator's non-linear model at each sampling instant.

$$\left.\begin{array}{l} x(k+1) = A.x(k) + B.u(k) \\ q(k+1) = C.x(k) \end{array}\right\} \qquad (6)$$

$$\left.\begin{array}{l} \min\limits_{\Delta U(k)}\left\{\left\|q^{d}(k)-q(k)\right\|_{\Psi}^{2}+\left\|\Delta U(k)\right\|_{\lambda}^{2}\right\} \\ \text{subject to}\begin{cases}-\Delta U_{\max}\leq\Delta U(k)\leq\Delta U_{\max} \\ U_{\min}-U(k-1)\leq J.\Delta U(k)\leq U_{\max}-U(k-1) \\ q_{\min}-q^{O}(k)\leq\Delta q(k)\leq q_{\max}-q^{O}(k)\end{cases}\end{array}\right\} \quad (7)$$

Where (6) represents the discrete state space linearized model, in which x is the state vector, A system matrix, B input matrix and C is the output matrix. Whereas (7) is the cost function, $\Delta U_x, U_x \in \Re^{n.N_u}$, U_x from equation (5) and ΔU_x is the maximum /minimum optimized increments N_u is the control interval. $q_x, q^o, \Delta q \in \Re^{output\ vector\ length}$ are the maximum / minimum admissible predicted joint angles specified by the manufacturer, free output joint angle and the forced output joint angle.

Simulation results:

Simulation under Un-constrained controllers:

1- Un-constrained PI-controller:

In this simulation, the goal is to achieve trajectory tracking with minimum input torque and acceptable overshoots. The controller parameters are determined from applying Nicolas tune method. Get the full oscillation ultimate gain K_u, with K_i=0, the proportional constants K_p= 0.45K_u, and integral reset K_i=1/1.2T_u where T_u is the oscillation period.

Figure 2 shows the tune results for determining K_u and T_u.

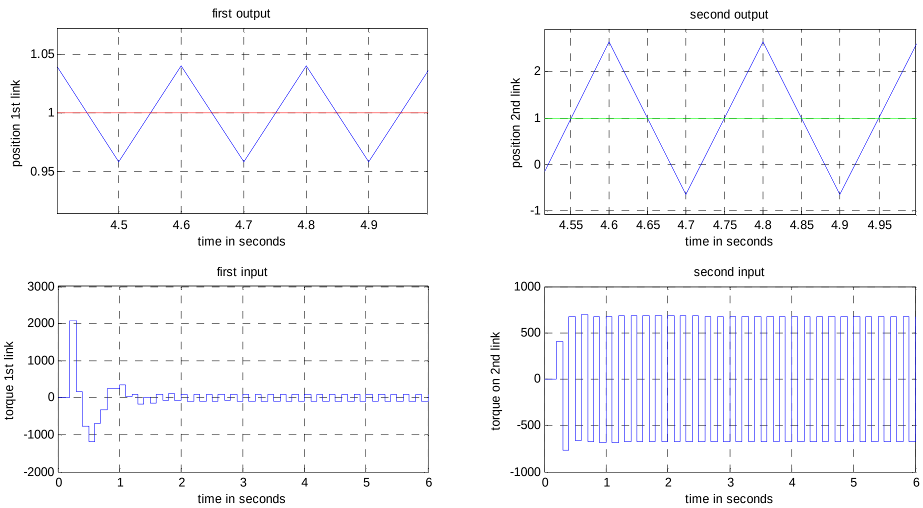

Figure: 2 joint angle oscillation and corresponding required torques

The tuned $K_u = \begin{bmatrix} 2080 & 0 \\ 0 & 407.7 \end{bmatrix}$, and from the figure $T_u = \begin{bmatrix} 0.2 \\ 0.2 \end{bmatrix}$.

Therefore, the controller parameters are: $K_p = \begin{bmatrix} 936 & 0 \\ 0 & 184 \end{bmatrix}$ and

$$T_i = \begin{bmatrix} 0.167 \\ 0.167 \end{bmatrix}$$

The simulation result with these parameter values (shown in figure 3), shows high overshoot (>40%) and relatively long settling time which is not recommended. It is noticed also that the applied input torques are quite high for first joint and as high as the upper limitation for the second joint. A proper tune is required

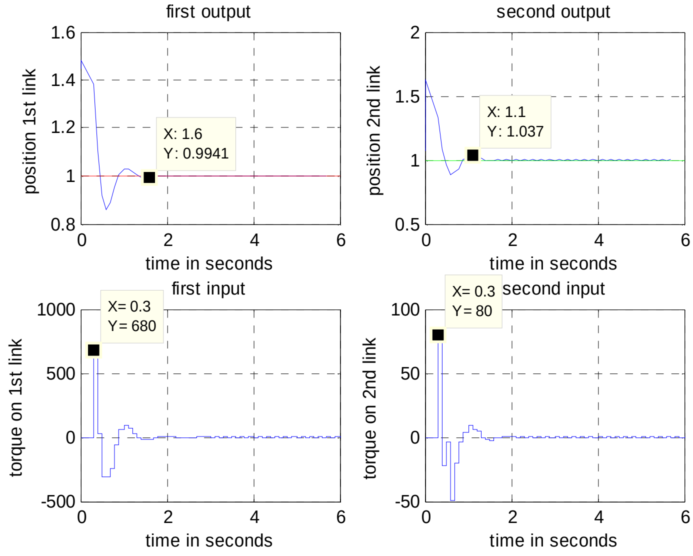

Figure: 3 joint positions and corresponding required torques, under PI-controller

Figure 4 shows the ISE criterion application for the angular position errors in the two joints.

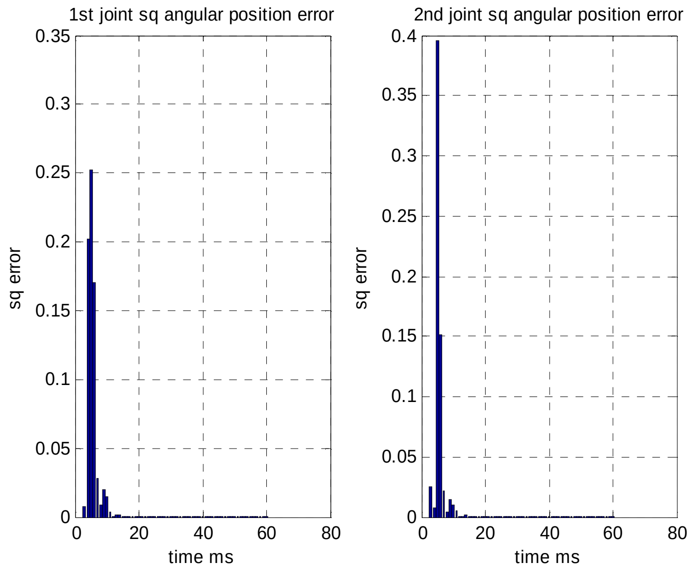

Figure: 4 joint squared position error under PI-controller

2- Simulation under Un-constrained MPC controller

The same simulation criterion is applied, i.e. trajectory tracking with minimum input torque and acceptable overshoots. The controller parameters were tune to achieve the goal. The simulation result shown in figure 5.

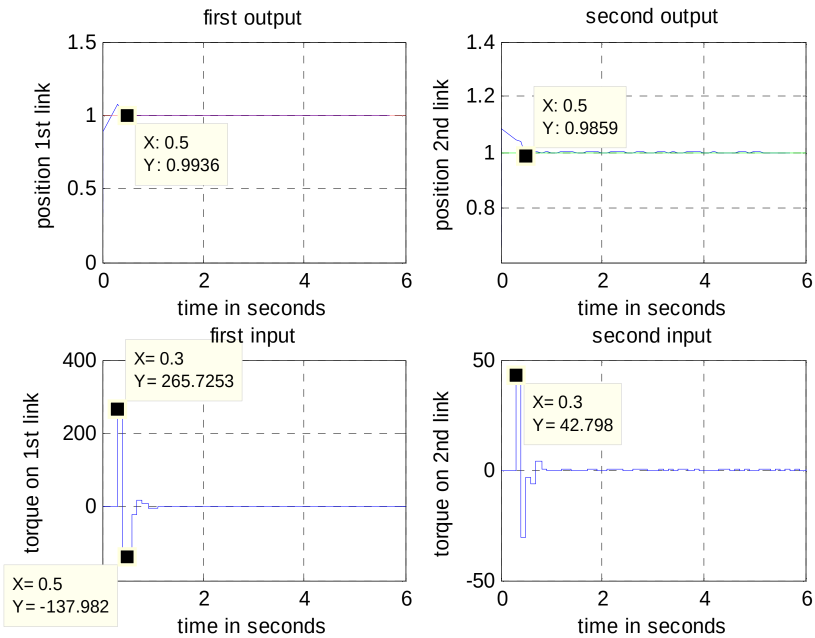

Figure: 5 joint positions and corresponding required torques under MPC

Figure 6 shows application of ISE criterion to angular positions under Un-constrained MPC controller.

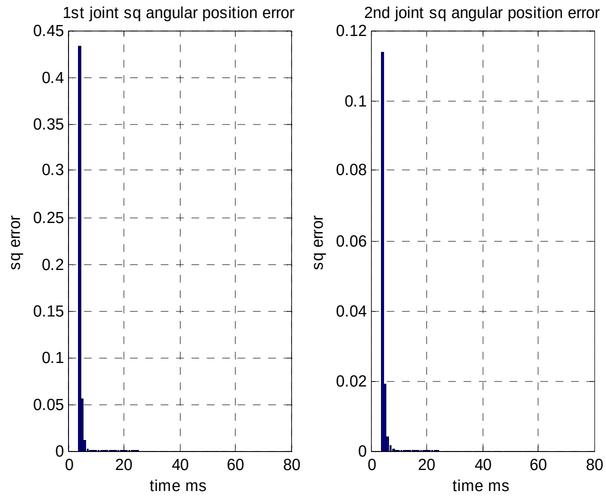

Figure: 6 joint squared position error under MPC

However, the magnitude of the ISE of the first joint is remarkably bigger in case of MPC, it is noticed that in general the un-constrained MPC performance is much better than counterpart PI-controller, particularly from required input torque and remarkable short settling time point of view.

Simulation results under constrained controllers:

1- Constrained PI-controller;

The same model used in the Un-constrained case is used with the restriction that the inputs of either joint obeys the technical input requirements.

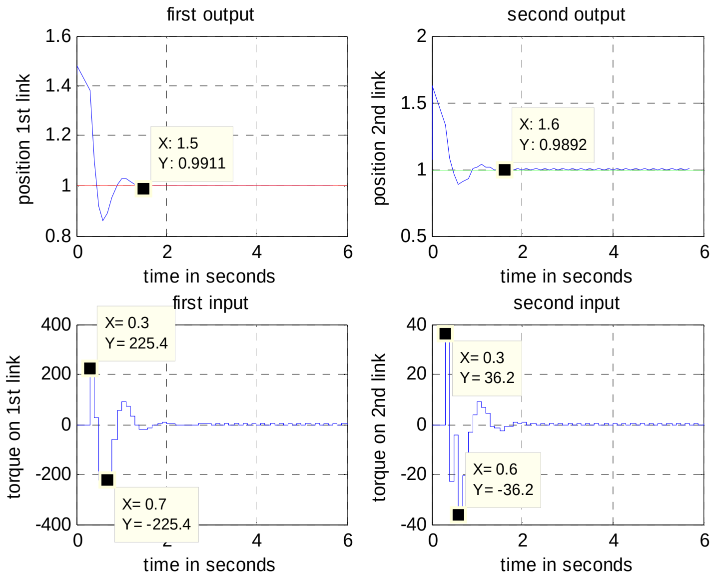

Figure: 7 joint positions and corresponding required torques under constrained PI

The application of the ISE criterion for the position errors under constrained PI-controller is shown in figure 8.

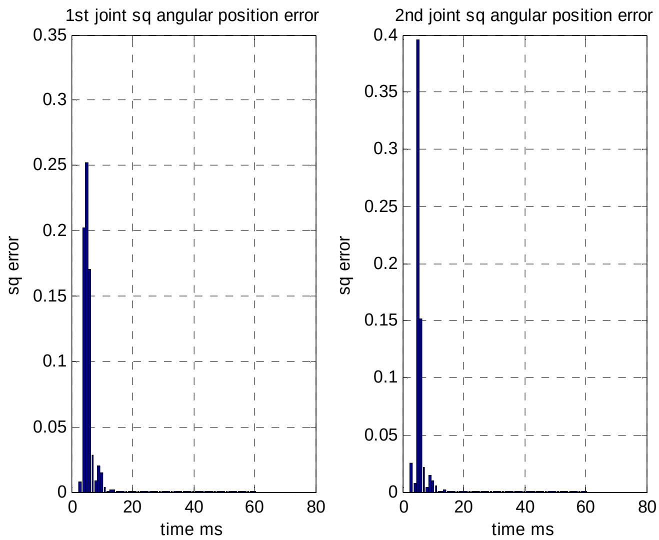

Figure: 8 joint squared error under constrained PI-controller

2- Simulation under constrained MPC-controller

Keep in mind that the target of simulation and the controller parameters unchanged. Apply the input torque technical specifications. Figure 9 shows the results of simulation, position tracking and corresponding required inputs.

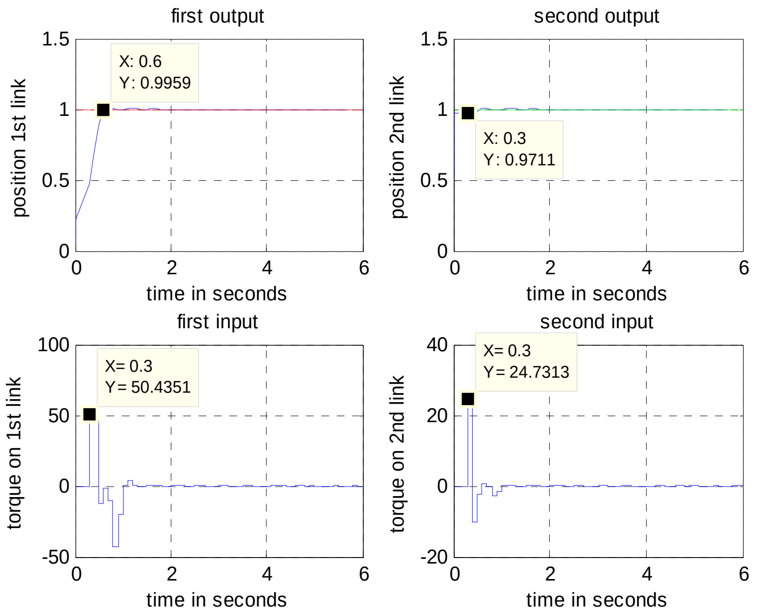

Figure 9 joint positions and corresponding required torques under constrained MPC

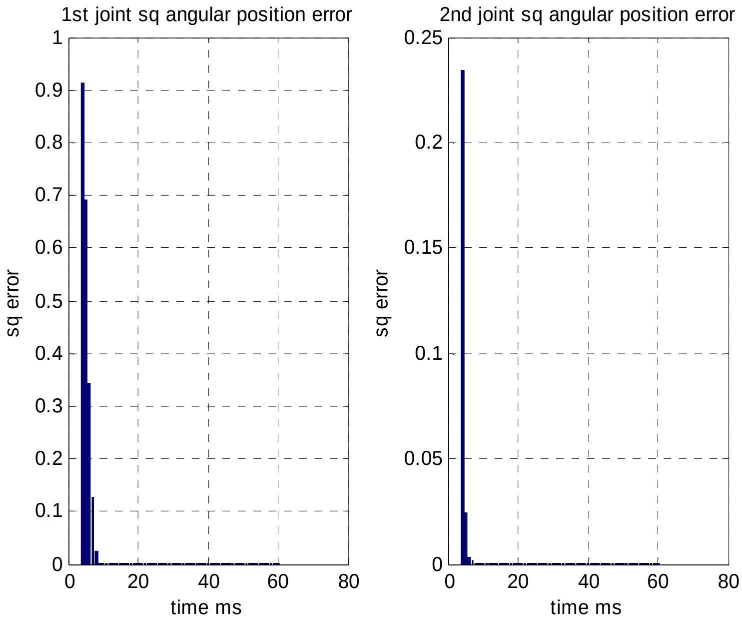

Figure 10 joint squared error under constrained MPC

Figure 10 shows the result of the application of the ISE criterion for the position errors under constrained MPC. No significance changes in comparison with un-constrained controller except for second joint which has much less accumulated error, this expected because of small input requirements.

Conclusion:

The classical PI-controller operates as SISO strategy and hence it is not insensitive to the coupling exists between the joint (dynamics) of the robot; however its performance is good in trajectory tracking. The MPC-controller is characterized by MIMO capability of operation and hence is insensitive to the coupling of the robot joints. The simulation results sustain the advantage of MPC technique to conventional PI. This is quite expected, because of the philosophy of operation of each of the two control schemes applied to high coupling (high non-linearity) inherited the direct driven manipulator.

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