Hybrid Connection Of Pid And Fuzzy Controller For Flexible Joint Robot With Uncertainties

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Abstract:

The performance of robotic system with PID controller that parameters are obtained by the different tuning methods will be improved in this paper by adding a simple fuzzy controller (FC) to the PID controller, so that this hybrid PID-FC connection can be used for controlling the robotic system under different uncertainties like variable load and external disturbance with very high specification response.

The suggested method is simple and not need huge computations. A single link flexible joint robotic system with uncertainties (variable load, external disturbance) is controlled by this method and by the different PID controllers (pole placement PID, pole-zero cancelation, and robust PID method) to show the efficient improvement for the suggested method on the specifications of system response, the flexible joint robotic system is tested by two types of desired inputs (nonlinear trajectory, and mixed linear trajectory).

Keyword: PID controller, tuning method, fuzzy controller, flexible joint robot, uncertainties, external disturbance, linear and nonlinear trajectory inputs.

ربط هجين ل PID و Fuzzy Controller للروبوت المرن بوجود الشكوك

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الخلاصة:

في هذا البحث تم تحسين أداء النظام الآلي المسيطر عليه من قبل وحدة التحكم PID والتي يتم الحصول على متغيراتها بواسطة طرق التعديل المختلفة عن طريق إضافة وحدة تحكم بسيطة غامض (FC) إلى وحدة التحكم PID، بحيث يمكن استخدام هذا الربط الهجين PID-FC للسيطرة على النظام الآلي تحت الشكوك مختلفة مثل الحمل المتغير والاضطرابات الخارجية وباستجابة عالية المواصفات.

الأسلوب المقترح هو بسيط ولا يحتاج الى حسابات ضخمة. تم اختبار نظام الروبوت ذات الذراع الواحدة المرن بوجود وعدم وجود الشكوك (حمل متغير، والاضطرابات الخارجية) بواسطة هذه الطريقة وبواسطة وحدات التحكم PID مختلفة (Pole placement PID method , pole-zero cancelation, and robust PID method) لإظهار كفاءة تحسين للأسلوب المقترح على مواصفات استجابة النظام، تم اختبار النظام الآلي المرن من قبل اثنين من أنواع المدخلات المطلوبة (مسار غير خطي، ومسار خطي مختلط).

I. Introduction

The Proportional-Integral-Derivative (PID) controllers are one of the most important control elements used in process control industry [1]. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows process engineers to operate them in a simple and straightforward manner [2]. But the parameters of the Proportional (P), the Integral (I), and the Derivative (D) in this controller it is not easy to be defined.

A huge number of methods for control design can be applied to PID control. There are number of special methods that are made by training for PID control have also been developed, these methods are often called tuning methods [3]. However, appropriately tuning a PID controller is not an easy task although it has only three parameters at most. The difficulty patricianly comes from some conflict requirements of control system performance and partially is due to complicated impacts of PID parameters on control performance [4]. [5] divided tuning methods into three classes, namely,

1) open loop tuning method like the Ziegler-Nichols step response method and the method using the characteristic areas of the step response.
2) closed loop tuning method like the Ziegler-Nichols closed loop method, Hazebroek- Waerden method, Methods based on relay feedback.
3) and intelligent method like Tuning method based on fuzzy inference scheme and tuning method based on expert system.

In other word, trajectory planning and control is important in robotic engineering and provides a significant application for systems control theory. A robotic system has very strong nonlinear characteristics and, often, contains variable system parameters in a real environment. Recently, experimental evidence indicates that joint flexibility should be accounted for in both modeling and control of many engineering robotic manipulators [6]. Therefore, the modeling of the flexible-joint robot is far more complex than that of the rigid robot. Since the mathematical model is only an approximation of the real system, the simplified representation of the system behavior inevitably contains model inaccuracies such as parametric uncertainties, unmodeled dynamics, and external disturbances. Because these inaccuracies may degrade the performance of the closed-loop system, any practical design should consider their effects. The inherent highly nonlinear coupling and model inaccuracies make the controller design for a flexible-joint robot extremely difficult [7].

Different approaches are suggested to treat these problems like [6, 8] which are suggest to use fuzzy controller to control the flexible joint with uncertainties, [7] suggest an adaptive sliding controller for a single-link flexible-joint robot with mismatched uncertainties. [9] present an application of the generalized predictive control to the single-link flexible joint robot. [10] give a survey of the advances and an assessment for future developments, concentrated mostly on the control issues of flexible joint robots.

Whatever, in this paper, the performance of the PID controller which parameters calculated by different tuning methods is improved by interacting the PID with simple fuzzy controller. The suggested hybrid connection of PID and fuzzy controller (PID-FC) is a simple method that will improve the output response specifications as we will explained in section IV which will give the details about the suggested method, the perfect response for the many simulation tests with the suggested method will illustrated in section V, finally the summary and conclusion will be presented in section VI.

II. Mathematical model for the single link flexible joint robotic system.

Consider a typical flexible joint robotic arm model shown in Fig.(1), described by [6, 8, 9]

$$\begin{aligned} &I\ddot{q}_1 + Mgl\sin(q_1) + K(q_1 - q_2) = 0 \\ &J\ddot{q}_2 + K(q_2 - q_2) = u \end{aligned} \qquad \text{.....(1)}$$

Where, q_1 is the link angular displacement and considered as the output to be controlled, q_2 is the motor angular position, I is the link inertial, J is the rotor inertia, K is the stiffness, M is the link mass, g is the gravity constant, and l is the center of mass. The control input u is the torque delivered by the motor.

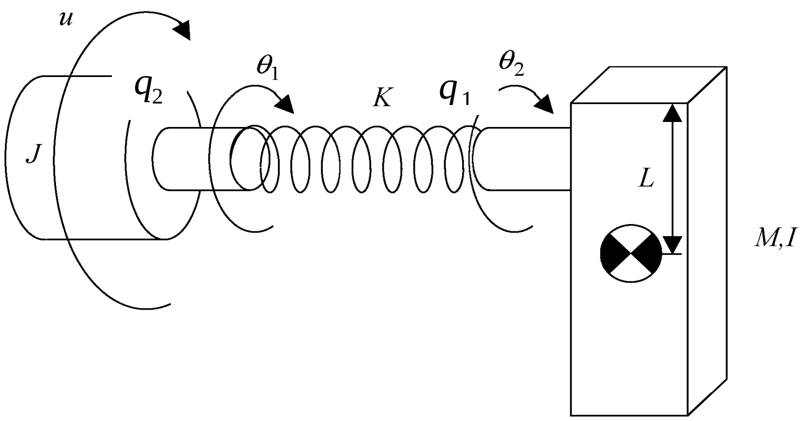


Fig.(1):single link flexible joint robotic arm [7].

The state variable dynamic equations for Eq.(1), are given by [7]:

$$\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = -\frac{Mgl}{I}\sin x_1 - \frac{K}{I}(x_1 - x_3) \\ &\dot{x}_3 = x_4 \\ &\dot{x}_4 = \frac{K}{J}(x_1 - x_3) + \frac{1}{J}u \end{aligned} \qquad \text{.....(2)}$$

Where x_i R, i=1,…,4 are state variables, and the output $y = x_1 = q_1$.

Using some simplification, the transfer function, in *s*-domain, of the system is given by [9]:

$$\frac{q_1(s)}{u(s)} = \frac{K}{IJs^4 + (IK + MglJ + KJ)s^2 + MglK} \quad .....(3)$$

The data that we used in this paper (which are taken from [8]) are:[I=0.030(kgm^2), J=0.004(kgm^2), Mgl=0.800(Nm), K=31.00(Nm/rad)]. With these data, Eq.(3) becomes:

$$\frac{q_1(s)}{u(s)} = \frac{31}{0.00012s^4 + 1.0577s^2 + 24.8} = \frac{258330}{s^4 + 88103s^2 + 206670} \quad .....(4)$$

Which has all poles on the imaginary axis: +93.7585i, -93.7585i, + 4.8487i, and - 4.8487i
A small gain can be added to the position or velocity feedback of the link (q_1) or the motor (q_2) for insure the internal stability for the robotic.

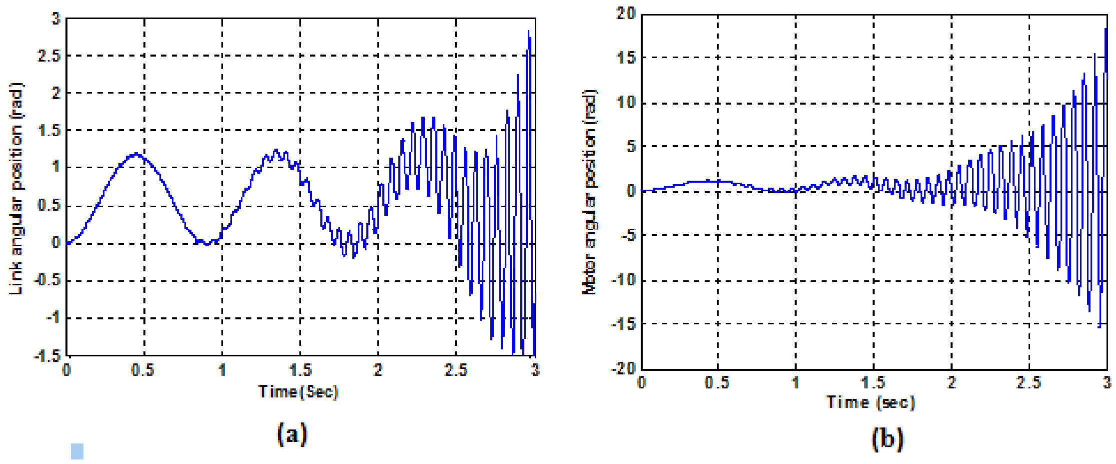


Fig.(2): The output response for the link angular position and the motor angular position without small gain.

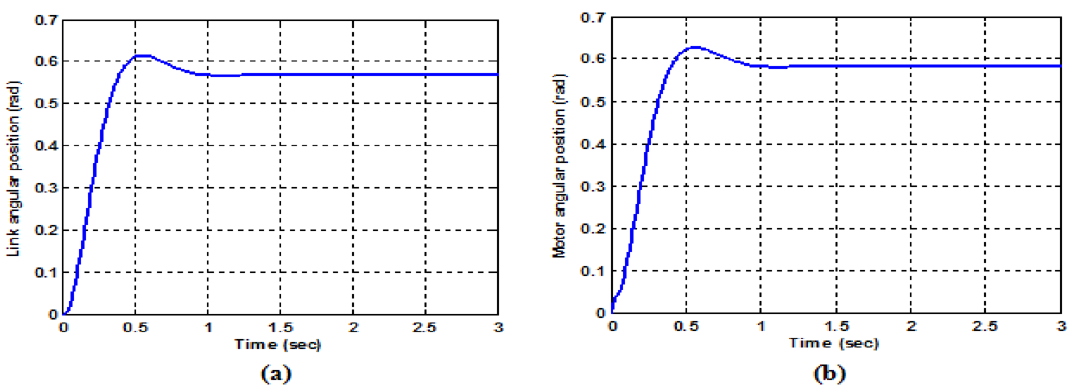


Fig.(3):The output response for the link angular position and the motor angular position with small gain in the motor feedback velocity.

In this paper we suggested to add a small gain (k_{dq_2} =0.3) to the velocity feedback of the motor variable. With Matlab simulink (version 7.12), the output response for the close loop robotic system without and with the small gain in the velocity feedback of the motor variable under unit step testing input signal are shown in Figure.(2) and Figure.(3).

As can be seen from the output response of the close loop flexible joint robot connection (Figure.(2)) that the robot system is unstable for both link and motor position. While with the small gain (Figure.(3)) the robot system became stable with steady state error $e_{s.s}$= 0.4310, M_p= 7.9086, t_s=0.5804 sec., t_p =0.5515 sec., for link position and $e_{s.s}$= 0.4171, M_p=7.5142, t_s =0.5804 sec., t_p=0.5604, t_s=0.824(base on 2% criteria) for motor position.

III. PID Controllers

PID stands for proportional-integral-derivative. The controller response combines three response mechanisms as a whole: proportional response {proportional to the gap between the reading and the set point, integral response {proportional to the integral of the changes between the past and present reading vs. the set point and derivative response {proportional to the rate of change of the reading. By adjusting the weights on the three responses, one can almost always insure a stable, fast reacting control dynamics [11].

As we mentioned in the introduction, the tuning parameter can be done by different tuning method, three PID tuned methods will be used in this paper, these methods are:

1) Pole-zero cancelation method.
2) Robust PID method.
3) Pole placement PID method.

In order to drive the PID controller parameters (K_p, K_i, K_d) to these methods in simple manner, we suggest to use the dominant pole simplification method with small modification to reduce the transfer of the flexible joint robotic system (Eq.(4)) to the following second order transfer function,

$$\frac{q_1(s)}{u(s)} = \frac{29.69}{s^2 + 22.52} \qquad \text{.....(5)}$$

The output response for the open loop and close loop connection for both original linear transfer function (Eq.(3)) and the reduced transfer function (Eq.(5)) are shown in Fig.(4). These figures show the agree in response for the both equations.

With the small gain (0.3) in the velocity feedback, equation (5) becomes;

$$\frac{q_1(s)}{u(s)} = \frac{29.96}{s^2 + 8.99s + 23.52} \qquad \text{.....(6)}$$

The output response for the open loop and close loop connection for both original nonlinear robotic equation with the small gain in the velocity feedback of the motor variable and the reduced transfer function (Eq.(6)) under unit step input are shown in Fig.(5). Figure(5-a) show small error between the response of the original robot equation (Eq.(1)) and the response of the reduced equation (Eq.(6)), while figure(5-b) show the agree in response for the both equations.

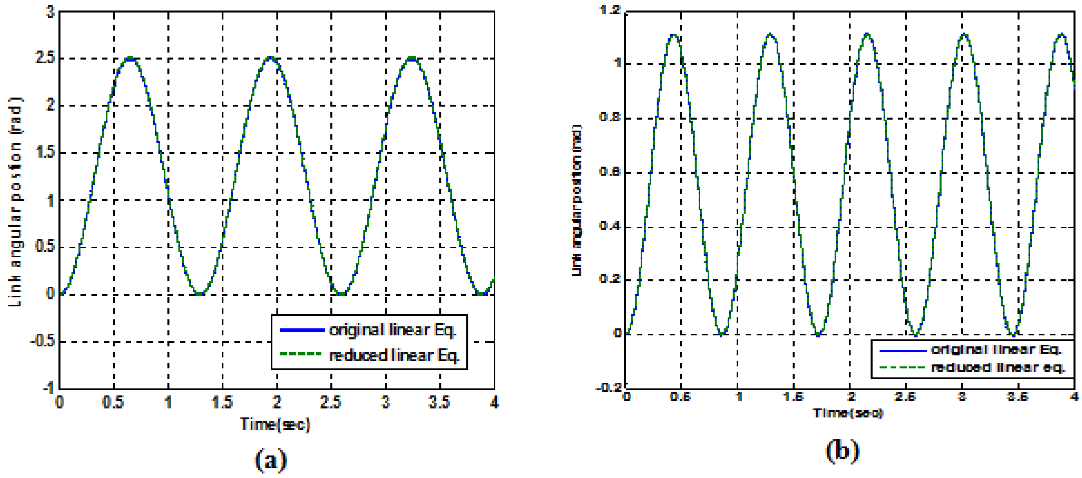


Fig.(4): a) Output response for open loop connection of original and reduced linear transfer function. b) Output response for close loop connection of original and reduced linear transfer function.

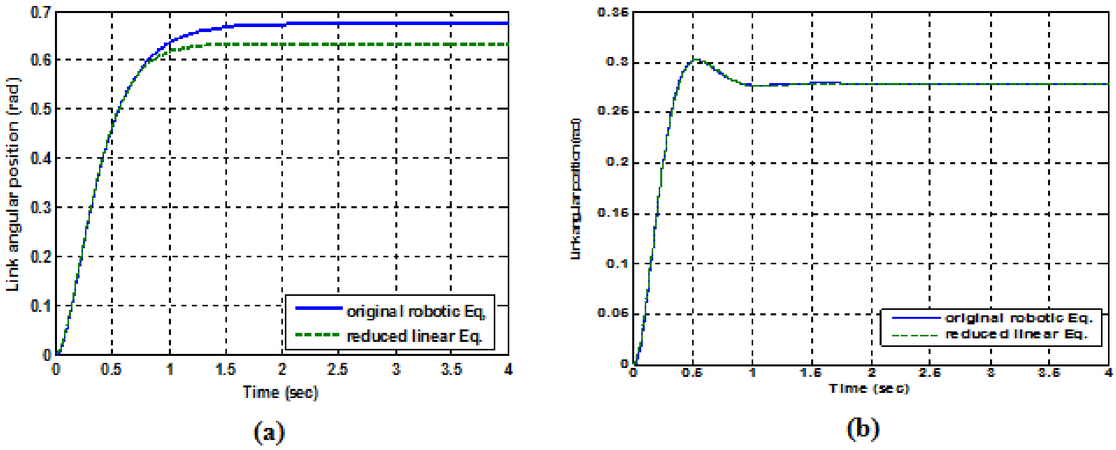


Fig.(5): a) Output response for open loop connection of original nonlinear robotic Eq.(1) and reduced linear Eq.(6). b) Output response for close loop connection of original nonlinear robotic Eq.(1) and reduced linear Eq.(6).

1) Pole zero cancelation method

With this method, the control parameters (K_p, K_i, K_d) can be determine from the reduce linear transfer function of the robot (Eq.(6)) by comparing the denominator of this equation with the numerator of the control equation ($(K_p s + K_i + K_d s^2)/s$) as illustrate by:

$$K_d s^2 + K_p s + K_i = s^2 + 8.99s + 23.52 \qquad \text{.....(7)}$$

From this comparison, K_d=1, K_p=8.99, and K_i=23.52, these parameters can be modified in order to obtain more perfect results, in this paper we change only the value of K_d to 1/3 instead of 1.

2) Robust PID controller method

Robust Control has low sensitivities and is stable over a wide range of parameter variations. It is economical and simpler to implement [12]. A Robust PID Controller design using Root Locus approach is presented in [13]. Consider a PID controller = $K_d(s^2 + as + b)/s$ where $a = K_p/K_d$ and $b = K_i/K_d$. Thus the PID Controller has a pole at origin and two zeros which can be placed anywhere in the left half s plane. PID controller is designed with complex conjugate zeros[12].

In this paper, we chose the complex zeros at $-6\pm j$. The open loop transfer function with PID controller will became:

$$G(s) = G_c(s)G(s) = \frac{K_d(s+6+j)(s+6-j)}{s} \cdot \frac{29.96}{s^2 + 8.99s + 23.52} \qquad \text{...(8)}$$

The root locus for this equation is shown in Fig.(6). The controller introduces a complex conjugate pair of poles at K_d above a certain value. With K_d=2, $a = \frac{K_p}{K_d} = 12$, so K_p=24, and $b = \frac{K_i}{K_d} = 37$ therefore K_i=74.

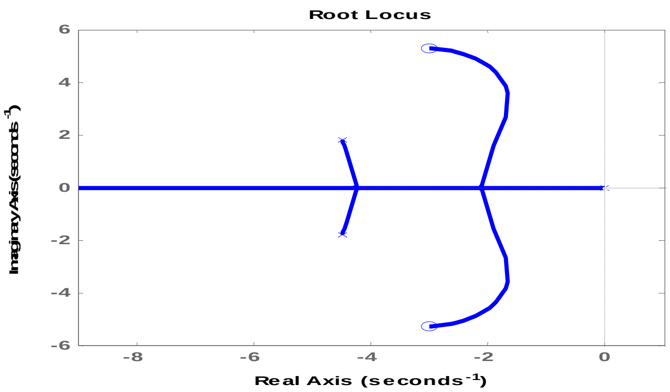


Fig.(6): root locus plot for the open loop transfer function with PID controller.

3) Pole placement PID controller

The design procedure for this method can be consists of three steps.

i) Select the a suitable closed –loop system by specifying the desired roots.
ii) Calculate the close loop equation for the controlled system ($G_cG/(1+G_cG)$).
iii) Determine the three coefficients of the PID controller by comparing the two equations.

the denominator equation of the suitable closed loop system is:

$$s^3 + as^2 + b^2 s + c = s^3 + 11.0869s^2 + 137.6077s + 60.928 \qquad .....(9)$$

The denominator (characteristic) equation ($1+G_cG$) for the controlled system:

$$1 + G_cG = 1 + \left(\frac{(K_p s + K_i + K_d s^2)}{s} \cdot \frac{29.96}{(s^2 + 8.99s + 23.52)} \right) \qquad .....(10)$$

$$= s^3 + (8.99 + 29.96K_d)s^2 + (23.52 + 29.96K_p)s + 29.96K_i$$

By comparing the Eq.(9) with Eq.(10), we obtain K_d=0.7059, K_p=3.808, and K_i=16.

IV. The Hybrid Connection PID-FC Methods

Figure(7) show the block diagram for the closed loop control system with the suggested controller method.

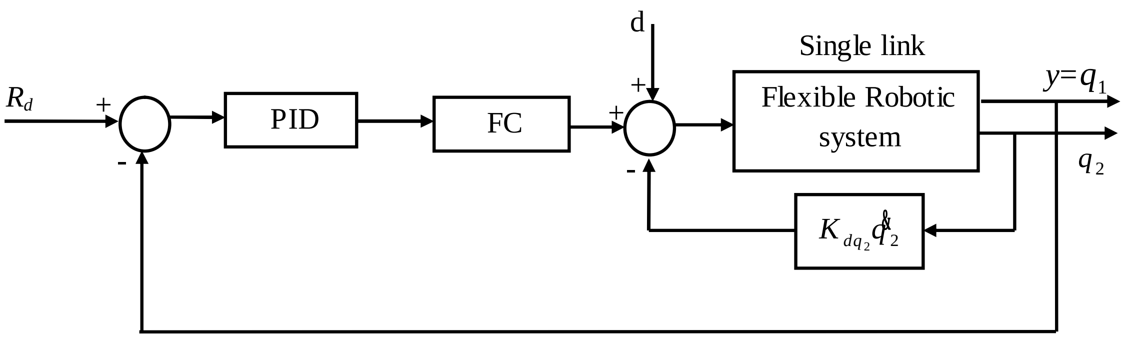


Fig. (7): the controlled plant with the Interaction PID-FC.

As shown from Fig.(7), the suggested controller consist from two controllers in interaction manner. The first controller is an ideal PID controller that parameters are driven from the three PID tuning method *i*) pole-zero cancelation *ii*) robust PID method and *iii*) pole placement PID method.

The second controller is single input-single output fuzzy controller, the input for this controller is the output of the PID controller which will has the following form(for linear desired trajectory):

$$i_f = (1 + \frac{1}{T_i s} + T_d s) \qquad ....(11)$$

And has the form(for nonlinear desired trajectory):

$$i_f = K_f (1 + \frac{1}{T_i s} + T_d s) \qquad ....(12)$$

Where K_f is a suitable constant gain. The fuzzy controller consist from three parts, these parts are:

1) Fuzzifcation: only three member ship function are suggest to represent the fuzzy controller input (i_f) and the output (u_f) as shown in Fig.(8) and Fig.(9) respectively. where N is negative, Z is zero, and P is positive, in the universe of discourse L_1 and L_2 respectively.

2) Rules: depended on the two suggested input member ship, the rule will be only three which are:

- If i_f is N the u_f is N
- If i_f is Z the u_f is Z
- If i_f is P the u_f is P

3) Defuzzfication: the Center of Mass (COM) formula [6, 8] is used to defuzzify the fuzzy control laws, so u_f with this formula becomes:

$$u_f = \frac{\sum \{input\ mempershipvalue \times mempershipvalue\ of\ output\}}{\sum \{mempershipvalue\ of\ output\}} \qquad ....(13)$$

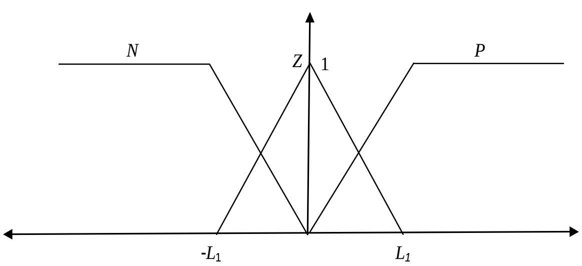


Fig.(8): The input membership functions for the FC.

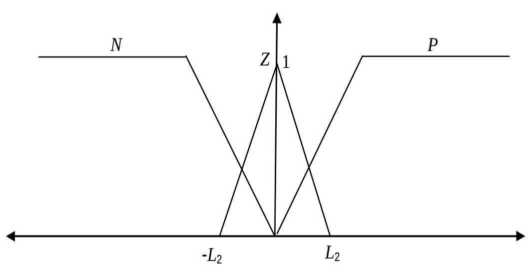


Fig.(9): The output membership functions for the FC.

V. Simulation Results

In this section, the complete close loop controller system (single link flexible joint robot with controller) are test by two desired trajectories with/or without uncertainties. The robot is controlled by two control methods: the PID controllers (pole-zero cancelation, robust PID method, and pole placement PID) and the suggested PID-FC in order to show the improve properties of the suggested methods on the robot performance. Note that, we select the value K_f=6 and L_1 =50, while L_2=80 with the three PID controllers.

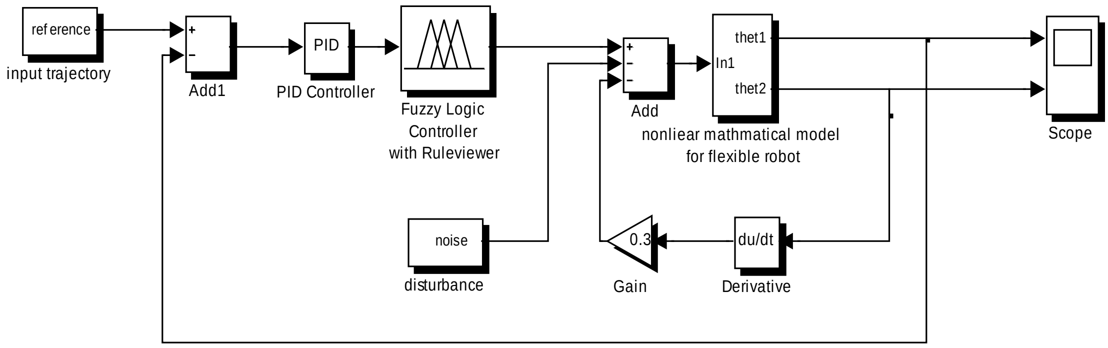


Fig.(10): the complete Matlab simulink connection for the controlled system with PID-FC.

The Matlab simulink connection for the complete close loop controller system with the suggested PID-FC is shown in Figure.(10), we will refer in simulation figures to desired reference trajectory as (Des), pole zero method as (PZ), robust PID method as (RM), and pole placement method as (PP).

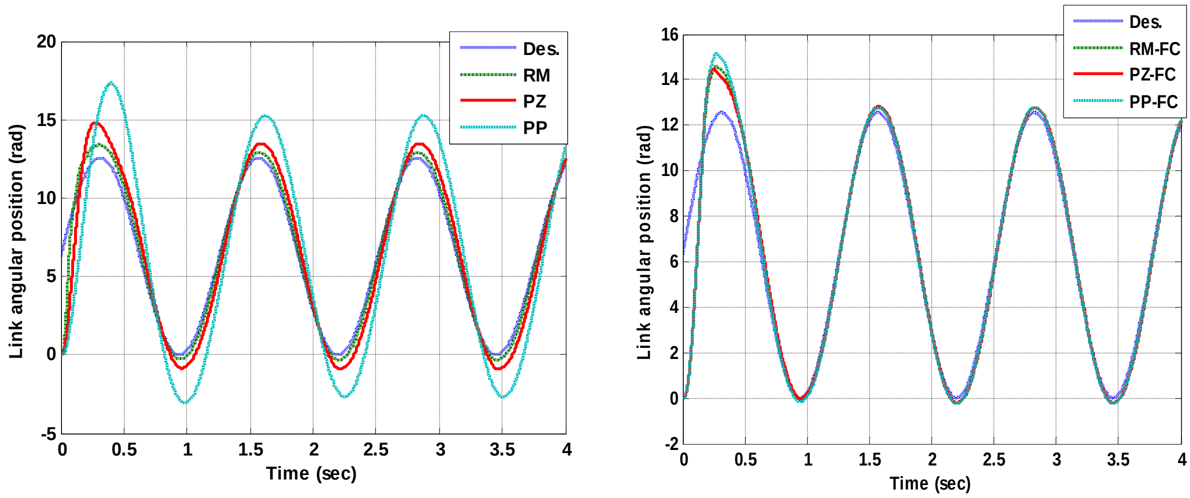
Different simulation cases are tested and as following:

- **test #1 : "nonlinear input with\without uncertainties"**

In this case, the nonlinear desired input trajectory (taken from [7]) which given by;

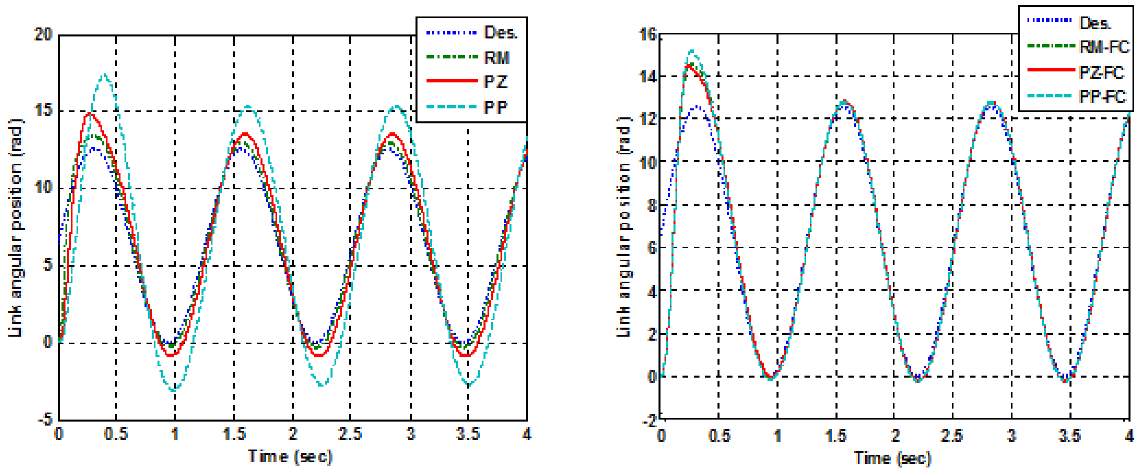
$$r(t) = 2p + 2p\,\sin(5t) \qquad \ldots.\ (14)$$

is used to test the performance of the flexible joint arm with the PID controllers and the suggested PID-FC method, the results for this test are shown in Fig.(11), while the simulation results for this trajectory and with random variable mass $M(t)$ load (from 0.1 to 1) are shown in Fig.(12).



(a) ***(b)***

Fig.(11):The output response for the flexible joint robot without uncertainty and with: (a)-PID controller. (b)- the suggested PID-FC.



(a) ***(b)***

Fig.(12): The output response for the flexible joint robot with time varying mass uncertainty and with: (a)-PID controller. (b)- the suggested PID-FC.

We can see from these results that the performance of robot with the suggested PID-OLC is more accurate in flow the desired input and with very small steady state error than the PID controllers. Also we can see that changing the value of robot mass has no effect on performance of the controllers (PID, or PID-FC).

- **test #2 : "*mixed input with\without uncertainties*"**

In this case, the linear mixed desired input trajectory (taken from [9]) which is: (reference angle value of $p/6$ until 2.5 sec., then a value of $p/3$ until 5 sec.) is used to test the performance of the flexible joint arm with the PID controllers and the suggested PID-FC.

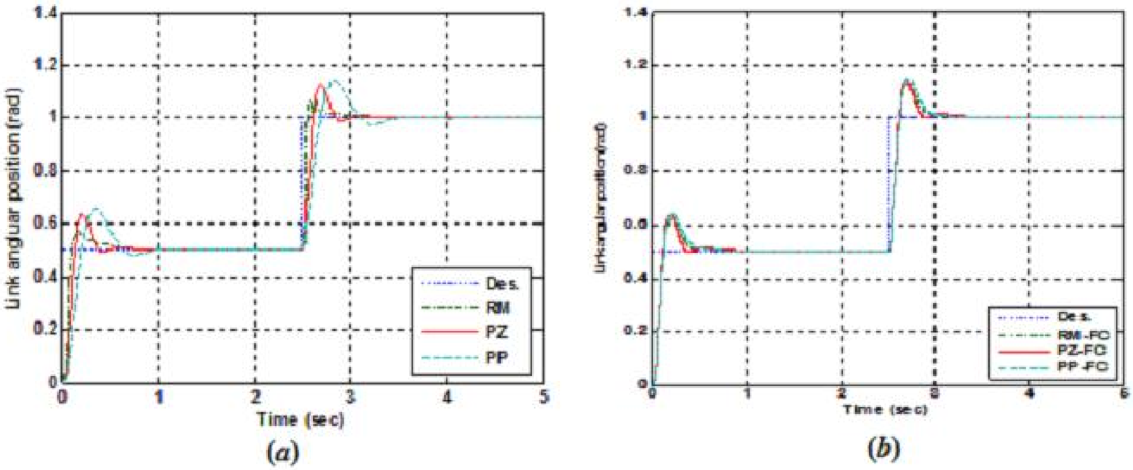


Fig.(13):The output response for the flexible joint robot for mixed input with no uncertainty and with:(a)-PID controller. (b)- the suggested PID-FC.

Firstly, the simulation results for this trajectory without any uncertainties are shown in Figure.(13). These results show that the performance of robot is good either with the PID-FC or with PZ, and RM controllers but the performance of the robot with PP-FC the is more accurate and fast in reaching the steady state than the PP controller.

Secondly, a step disturbance of value $p/20$ is added to the output robot, the simulation results for this test are shown in **Figure.(14),** We can see from these results that the performance of robot arm with the suggested PID-FC or with the PID controllers is still same as when there is no disturbance, this is may be because the value of disturbance is small value.

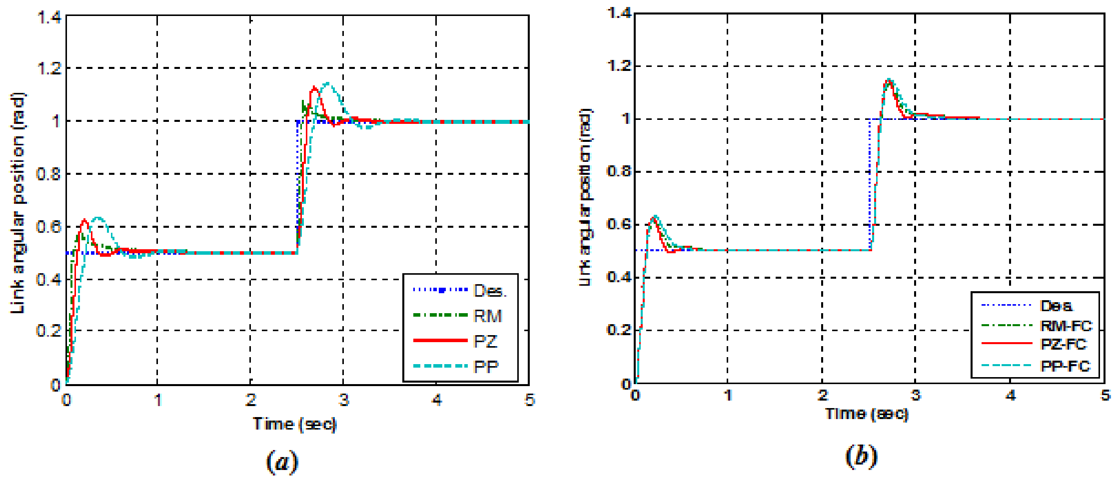


Fig.(14):The output response for the flexible joint robot for mixed input with step disturbance and with: (a)-PID controller. (b)- the suggested PID-FC.

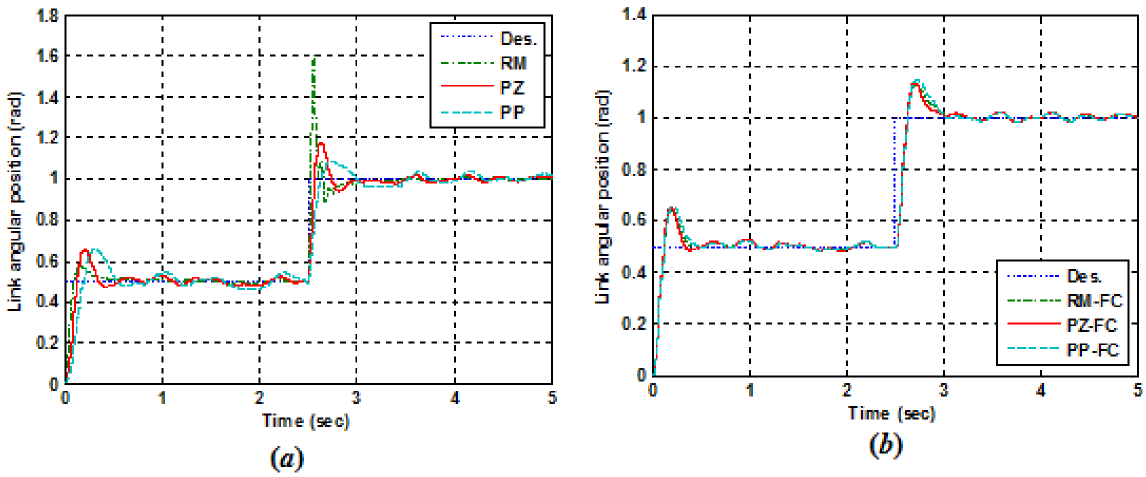


Fig.(15): The output response for the flexible joint robot with small random disturbance and with;(a)-PID controller. (b)- the suggested PID-FC.

Finally, a small random disturbance (-0.2 to 0.2) is added to the control signal, the simulation results for this test are shown in Fig.(15), We can see from these results that the performance of robot arm with the PID or with suggested PID-FC is accurate in flow the desired input, but with PID-FC the performance of robot is more fast in reduce the effect of the disturbance rather than with the PID controllers.

VI. Summary and Conclusion

In this paper a simple and efficient hybrid PID with simple fuzzy controller (FC) has been suggested in order to improve the performance of the different PID controllers which parameters are determine by pole-zero cancelation, pole placement PID, and robust PID controller method, and hence the new hybrid connection PID-FC methods make the output response of the tested plant more accurate in tracking the desired input with zero or very small steady state error. The suggested method applied on single link flexible joint robot. Different simulation cases with the suggested method and with the PID methods are tested with nonlinear trajectory, and mixed input trajectory, also two type of uncertainties (external disturbance, and time varying load(mass)) are include to show the efficiency of the suggested method which is simple and not need huge computation.

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