Position Control of Series Elastic Actuator (SEA) Using MATLAB Simulink

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Abstract:

Analysis of modeling and Simulink of Series Elastic Actuator (SEA) to improve the dynamic characteristics of displacement control and the possibility of using Arduino and Simulink in MATLAB program for the purpose of system control have been presented. This paper investigates the design of elastic series actuator and a model has been Proposed for the active one degree of freedom (Mass, spring, Damper) system focused on the transient behavior of the system. The proposed analysis tends to Produce a fast transient response to a step command, a zero steady-state error, low overshoot, and make the system less sensitive to disturbance as well as a short settling time used by PID controllers. Theoretical study and experimental investigation using a test rig built for this purpose has been achieved to examine the performance of the proposed Series Elastic Actuator (SEA) system. The performance is successfully validated in experiments using a quarter series elastic actuator (SEA) test rig for the active system. The theoretical and experimental results show that the used PID controller in the closed feedback loop control has led to a significant improvement in the results as well as reduce the response time of the system. Where the maximum overshoot is reduced to (7.14%), steady state error is approached to zero and settling time is reduced greatly to (2.59 sec).

Keywords: Series Elastic Actuator, PID Controller, Simulink MATLAB, Arduino.

1. Introduction

A Series Elastic Actuator is an actuator that has an elastic element intentionally placed between the actuator and the load where the deflection occurs in the elastic element can be measured to provide an accurate estimate of the force.

Fig. 1 Schematic view of a Series Elastic Actuator (SEA)

The elastic element added to the output side of the D.C motor [11].as shown in the figure (1).The function of the SEA is generated by elastic energy, and its control is high accurately as required [3]. This paper will focus on one degree of freedom only where the primary aim of this paper is to investigate the dynamic characteristics (Time constant, Transfer Function, Settling time, Rise time, Frequency Response, Dynamic error, Bandwidth, Speed of response, Cut off frequency) of the series elastic actuator and utilize the results to improve the mechanical design of the actuators, and study tracking error between the different responses that produced from the series elastic actuator and the desired displacement through using PID controller [4] which is a generic control loop feedback mechanism (controller) widely utilized in industrial control systems. Series elastic actuators offer many advantages in force control of robots in the unconstrained perimeter. These advantages include extremely low impedance, low friction, force fidelity, and good force control bandwidth and Shock tolerances [1]. A compliant element (spring) is placed between the gearbox and the driven load to intentionally reduce the stiffness of the actuator. Most studies used to investigate the series elastic actuator in last years are divided according to stiffness into two main categories: linear and nonlinear, and according to control into four categories: position control, velocity control, torque control and cascade control. The concept of series elastic actuation (SEA) has been primarily investigated by Morison and Kunduz [9]. The claim that the main advantage of inserting an elastic element at the output of an actuator is that it raises the quality of force control. This sort of actuation discrepancy with conventional robotic actuation which is focused maximizing stiffness to find high control bandwidth and small tracking errors. Yahya [8] studied the position control of the DC motor. Controlling the position of a DC motor is very important, such that any small change in position can drive to the instability of the closed-loop system. Traditional PID controllers are utilized to control the DC motor for different industrial processes for many years because of their simplicity in operation.PIC microcontroller employed as an application for PID controller. Thomas, Neenu, and Poongodi [10] utilized trial and error method to obtain optimal (PID) parameters (Proportional, Integral and Derivative) by attempts to correct the error between the desired position and the measured position through calculating the error and then outputting a pulse width modulated (PWM) voltage that can set the position accordingly. [5] Studied the position of control as the most important element in recent robotic and industrial applications. The simulated design is tested by utilizing different toolboxes in MATLAB/Simulink environment (library browser). From the previous works, the following notes can be concluded:

1. The conventional Series Elastic Actuator (SEA) system was widely investigated to study the design and adaptive control of the (SEA) system and to improve the performance of the robots that enter the (SEA) system in its combinations.

2. The experimental investigations utilizing test rig (SEA) system are very limited, especially for the active (SEA) system because of the cost, complex and difficult in the specification of the required measured data and in the building of the test rig. Therefore, most of the researchers were studied the active (SEA) system by theoretical simulation.

3. In most previous researches, the MATLAB / Simulink program is used to study and analyze the control system.

2. Experimental Work

Describes the control structures utilized in the experiments and how to use Simulink support package for Arduino Hardware in MATLAB and the measurements carried out on one degree of freedom of the series elastic actuator are listed as follows:

2.1 Rig (Required Hardware used)

- D.C Motor (actuator)
- Arduino MEGA 2560
- H-bridge
- Potentiometer (sensor)
- Accelerometer (sensor)
- USB Cable& Breadboard
- Solderless jumper B

2.1.1 Dc Motor & Gear Box

DC motor is a device used to convert electrical energy into mechanical energy and it is a versatile and also flexible machine [7]. So it can satisfy the request for high load at the starting, accelerating and retarding torques. A DC motor machine is easily adaptable for drives with a range of speed control and fast reversal. They are vastly used in industrial application. The DC motor used in the construction process of (SEA) of a small size has a maximum amount of voltage of 12+ volts is sufficient to meet the purpose required from it .the gearbox is very important and is a key part of the system. Gears are one of the most pivotal components in mechanical power transmission systems [12].The gears are mostly utilized to transmit power or torque, and the efficiency of transmission is very high when compared to another kind of transmissions. It enables us through its design to control the speed, the magnitude of torque and the force to be transported between the actuator and the system as well as the type of linear or rotational motion and direction. In the figure (2) show the gear used.

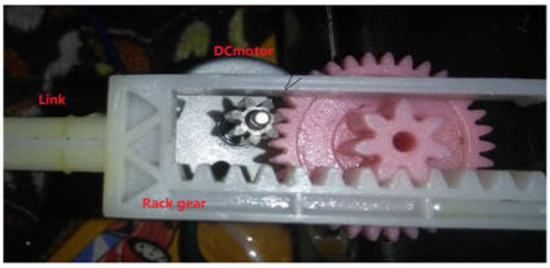

Fig. 2 DC Motor and Gearbox

2.2 Preparation and Assembly of the Series Elastic Actuator (SEA)

Construction of mechanical parts, electronic parts, and electrical circuits' structure and connection are as shown in Figure (3).

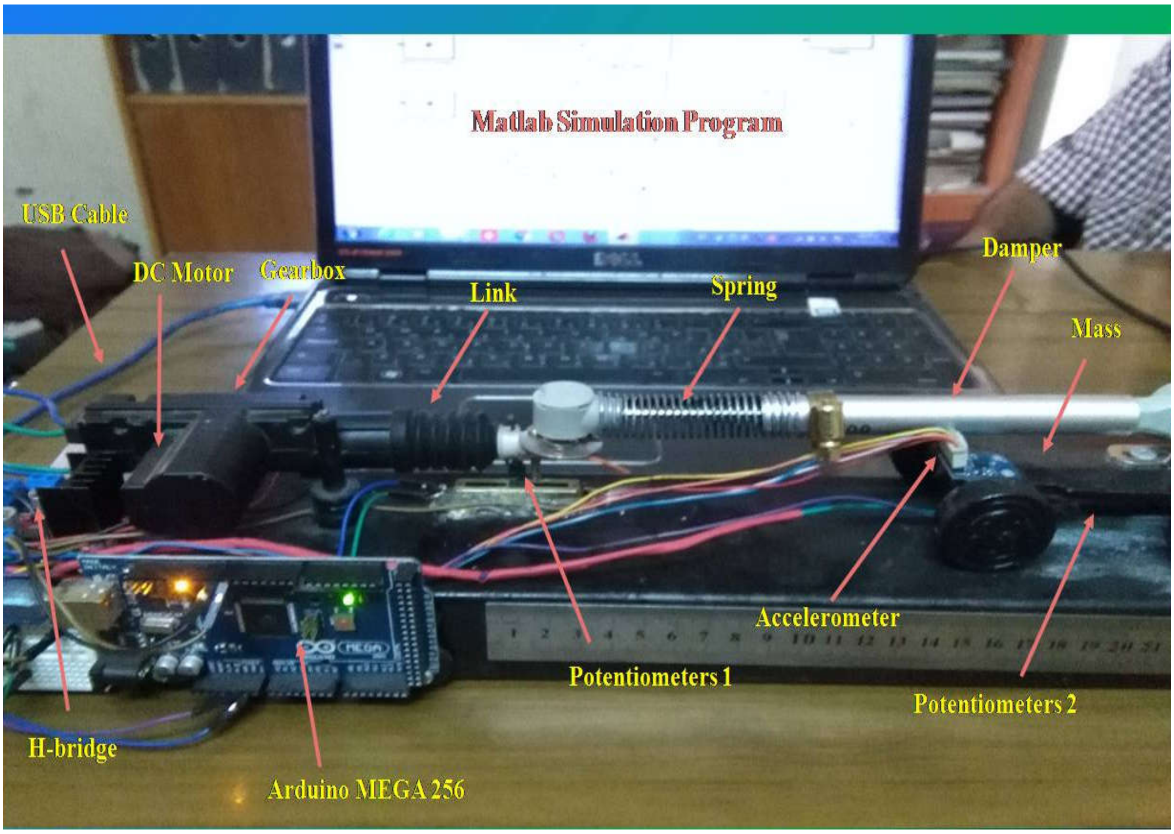

Fig. 3 Test Rig for Series Elastic Actuator (SEA)

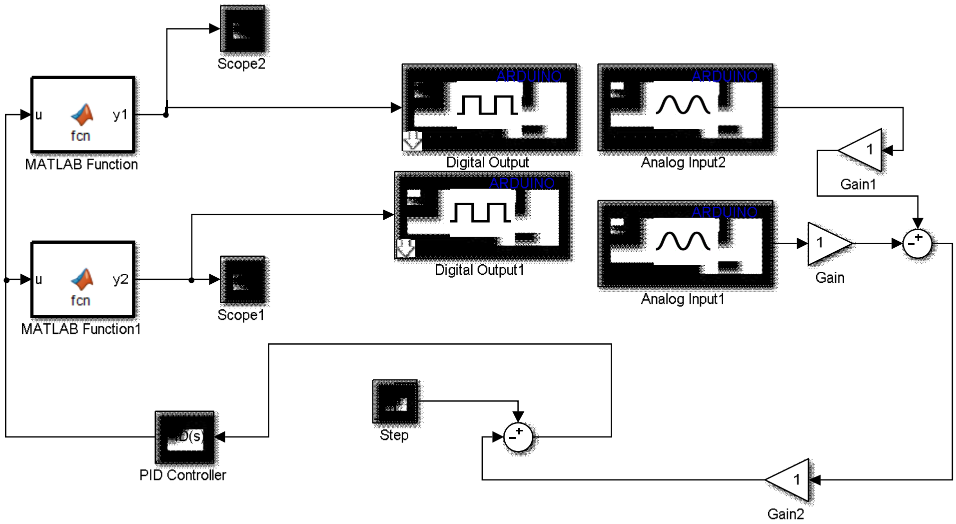

Fig. 4 Structure The operational control designed to simulate the system

2.3 Operation the System (Required software)

MATLAB program is one of the most popular programs that have been widely used in the analysis and simulation of control systems through containing a wide range of tools and settings as well as a huge array of mathematical functions that become essential in the application and analysis of control systems. Supported package for Arduino Hardware Contains a large library of elements that are used in the simulation. In Fig 4, the structure of the system (series elastic actuator) control has been simulated.

3. Modeling of the Series Elastic Actuator (SEA)

3.1 DC motor

Mathematics are utilized to describe the behavior of a system. A separately excited DC motor is utilized as a plant to the control system. The armature control method has been chosen. Furthermore, a Separately Excited DC motor has independent voltage supplied to the field and armature windings such that this structure type gives the advantage of more control on the motor performance [2].

The following equations describe the dynamic behavior of the actuator (DC motor) with single lumped inertia [6]. The Kirchhoff's equation can be written as:

$$v_a = R_a . i_a(t) + L_a . \frac{d\, i_a(t)}{dt} + V_b(t) \qquad (1)$$

The generated voltage or Back EMF (V_b) is relative to angular velocity:

$$V_b(t) = k_b . \omega(t) \qquad (2)$$

Sub equation (2) in (1)

$$v_a = R_a.i_a(t) + L_a.\frac{d\,i_a(t)}{dt} + k_b.\omega(t) \qquad (3)$$

Where:
v_a: Voltage of armature (volt)
R_a : Resistance of armature (Ω)
L_a: Inductance of armature (H)
V_b: Back EMF (volt)
i_a: Current of armature (amp)
ω: Angular speed (rad/s)

The armature current related to its motor torque (T_m) by:

$$T_m(t) = k_t.i_a(t) \qquad (4)$$

Newton's equation: -

$$T_m(t) = J\frac{d\,\omega(t)}{dt} + B.\omega(t) \qquad (5)$$

Sub equation (4) in equation (5): -

$$k_t.i_a(t) = J\frac{d\omega(t)}{dt} + B.\omega(t) \qquad (6)$$

Where:
T_m: Motor Torque (N.m)
k_b : Back EMF Constant (V/rad/S)
k_t : Torque Constant (N.m/Amp)
J : Inertia of Rotor (Kg.m^2)
Θ: Angular Position of Rotor Shaft (rad)
B: Viscous Friction Coefficient (Nm/rad/s)

From equation (6):

$$i_a(t) = \frac{J}{k_t}\frac{d\omega(t)}{dt} + \frac{B}{k_t}\omega(t) \qquad (7)$$

Sub in equation (3):

$$v_a = \frac{R_a}{k_t}\left|J\frac{dw(t)}{dt} + B\omega(t)\right| + \frac{L_a}{k_t}\left|J\frac{d^2\omega(t)}{dt^2} B\frac{d\omega(t)}{dt}\right| + k_b.\omega(t) \qquad (8)$$

Sub $\omega(t) = d\Theta/dt$

$$v_a = i_a\frac{J}{k_t}\frac{d^3\theta}{dt^3} + \left[R_a\frac{J}{k_t} + L_a\frac{B}{k_t}\right]\frac{d^2\theta}{dt^2} + \left[R_a\frac{B}{kt} + k_b\right]\frac{d\theta}{dt} \qquad (9)$$

3.2Transfer Function of DC motor

Using Laplace transforms, the above equation (9) can be expressed in Term of (s) [13].Thus, the transfer function between shaft position and armature voltage at no-load is:

$$\frac{\theta(S)}{V(S)} = \frac{k_t}{[(L_a J)s3 + (R_a J + L_a B)s2 + (R_a B + k_b k_t)s]} \qquad (10)$$

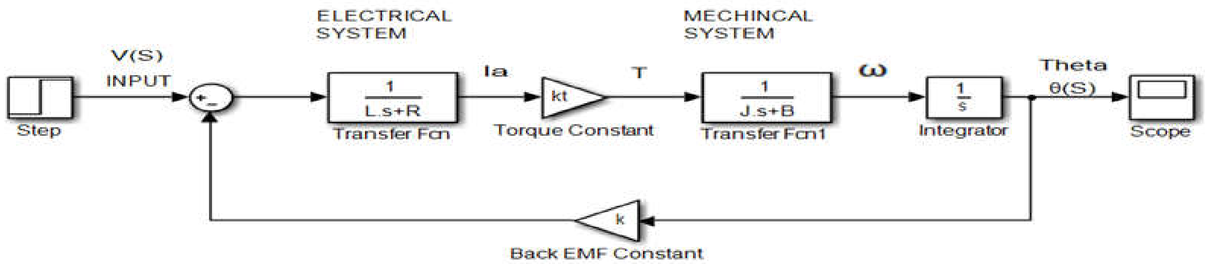

Fig. 5 A Closed-loop System That Representing the DC Motor

3.3 State Space of the DC Motor

The equations above can also be represented in state space from. Armature current, velocity motor and Position motor as our variables. Thus, the equations can be written as:

$$\frac{d}{dt}\begin{bmatrix}\theta\\ \omega\\ I\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & -\frac{B}{J} & \frac{k_t}{J}\\ 0 & -\frac{k_b}{L_a} & -\frac{R_a}{L_a}\end{bmatrix}\begin{bmatrix}\theta\\ \omega\\ I\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \frac{1}{L_a}\end{bmatrix}V \qquad (11)$$

The output from plant position (Θ) when the input voltage (v) is:

$$x=[1 \quad 0 \quad 0]\begin{bmatrix}0.42\ \theta\\ \omega\\ I\end{bmatrix} \qquad (12)$$

3.4 Dynamics modeling of system (spring, damper, and mass)

The motion of the body in a spring, mass, damper system depends on its spring stiffness, mass, damping Coefficients and applied forces.

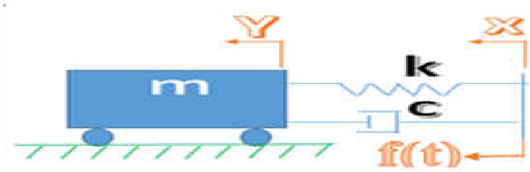

Fig. 6 Displacement Coordinates of the System

To obtain the equation of motion, Newton's second law is used as following:

$$m\frac{d^2y}{dt^2}=-k_s(y-x)-C\frac{d}{dt}(y-x) \qquad (13)$$

Where:-

m: Mass (kg)

c: Viscose damping coefficient

x: Input displacement (mm)

y: Output response (mm)

k_s: Stiffness spring constant

$$m\frac{d^2y}{dt^2}+c\frac{dy}{dt}+k_s y=c\frac{dx}{dt}+k_s x=f(t) \qquad (14)$$

3.4 State Space for (Spring, Damper and Mass) System:

Let

$$x_1 = y \qquad (15)$$

$$x_2 = \dot{y} \qquad (16)$$

Sub in equations (2):

$$\frac{d}{dt}x_2 = \frac{1}{m}[-cx_2 - k_s x_1 + f(t)] \qquad (17)$$

$$\frac{d}{dt}\begin{bmatrix}x_1\\x_2\end{bmatrix} = \frac{1}{m}\begin{bmatrix}0 & 1\\-k_s & -c\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}0\\1\end{bmatrix}f(t) \qquad (18)$$

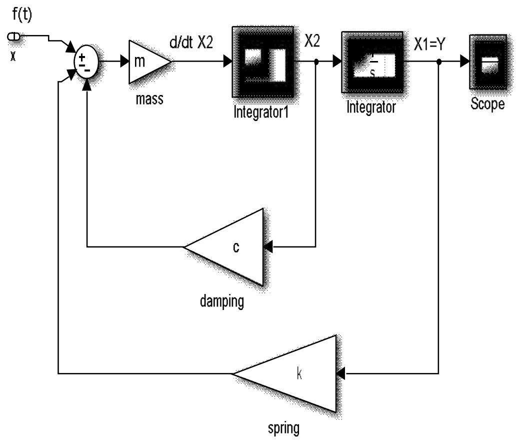

Fig. 7 Block Diagram for Passive System (spring, damper, mass)

$$Y = \frac{1}{m}[0 \quad 1]\begin{bmatrix}x_1\\x_2\end{bmatrix} \qquad (19)$$

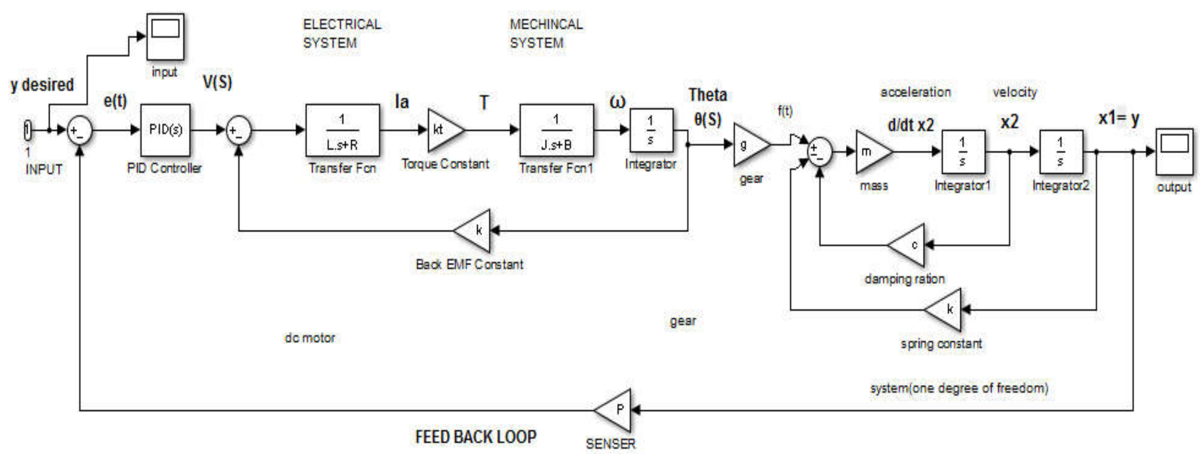

Fig. 8 Series Elastic Actuator Block Diagram (Closed Loop System)

4. Results and Discussion

4.1. Results Simulation of the DC Motor

A DC motor appears as a spring at high frequencies, which is much more flexible for collisions and other sudden changes. Figure (9) shows the simulation of the actuator (DC motor). The input to the system is selected as a unit step and the values of the angular velocity and angular displacement (angle) is determined.

The relation between the response and time is shown in Figure (10).The results show a simulated sine wave of decreasing velocity to settle at zero. This indicates that the value of the displacement has become constant and since the speed represents the derivative of the displacement, the speed should be zero. While for the angular displacement, the value is approaching the desired value at the beginning until it stabilizes to a Value less than the desired value and Can be tilted as a percentage:

$$\theta = 0.936\ \theta_{des}$$

This means that the error in angular displacement is 6.4 % which is consider a high value. The time that has taken to reach this value is also relatively large. Therefore; (PID) controller is used to reduce the error value to 3.4 % and reduce the settling time (the time required to reach the desired value).There is only one oscillation before the DC motor goes to the desired position, instead of four oscillation without the PID utilized. While the peak amplitude reduces to 1.3 instead of 4.85, the settling time was reduced by a third, as shown in Figure (11). This figure shows that the system will be stable after 3 sec, while the peak amplitude is 1.3 at 0.5 sec when PID controller is used.

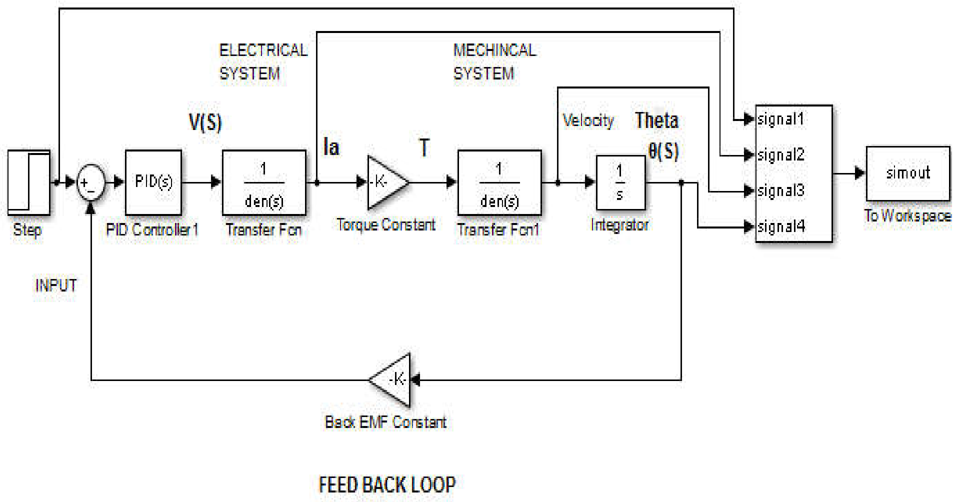

Fig. 9 Simulink of the DC Motor.

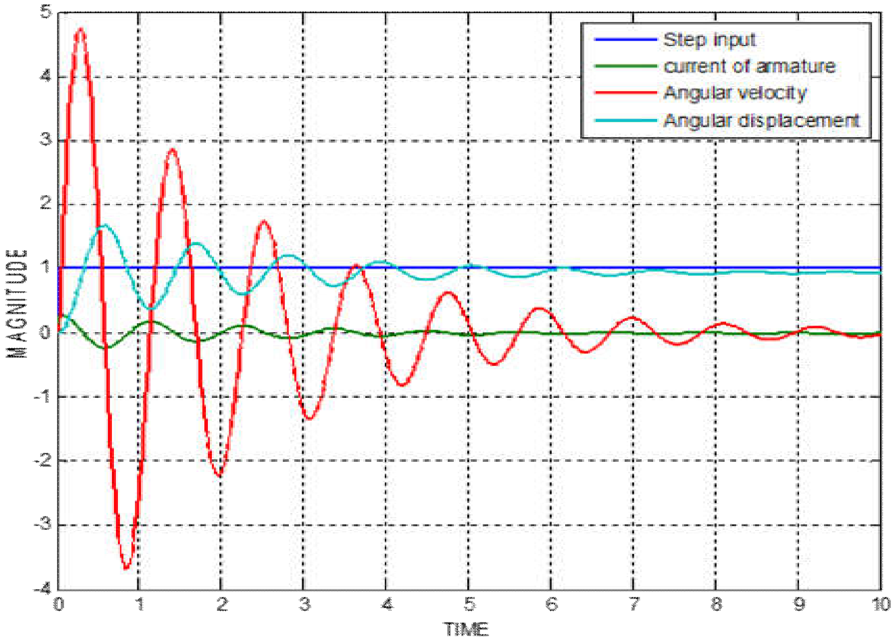

Fig. 10 Results of the DC Motor Simulink during 10 sec without PID Controller

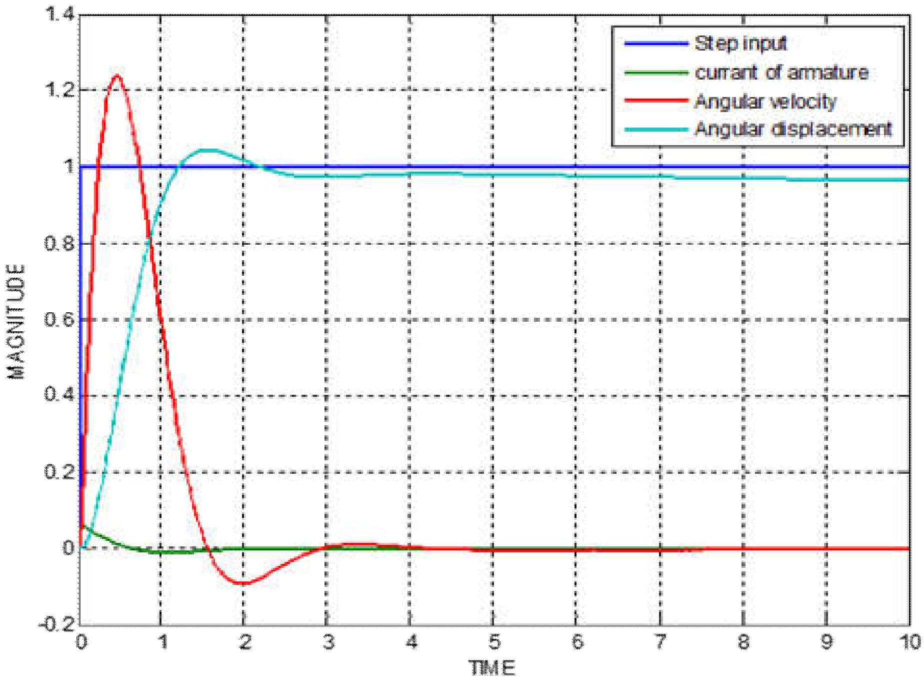

Fig. 11 Results of the DC Motor Simulink during 10 sec with PID controller

4.2. Dynamic characteristic of the (SEA) with PID controller

The maximum overshoot represent first peak on the SEA graphs. The initial positive peak is due to the DC motor leading the mass, which is expected since the DC motor needs to tension the linear spring before the spring generates enough force to move the mass. The simulations in figure (12) show a greater reduction in the maximum overshoot of the system.

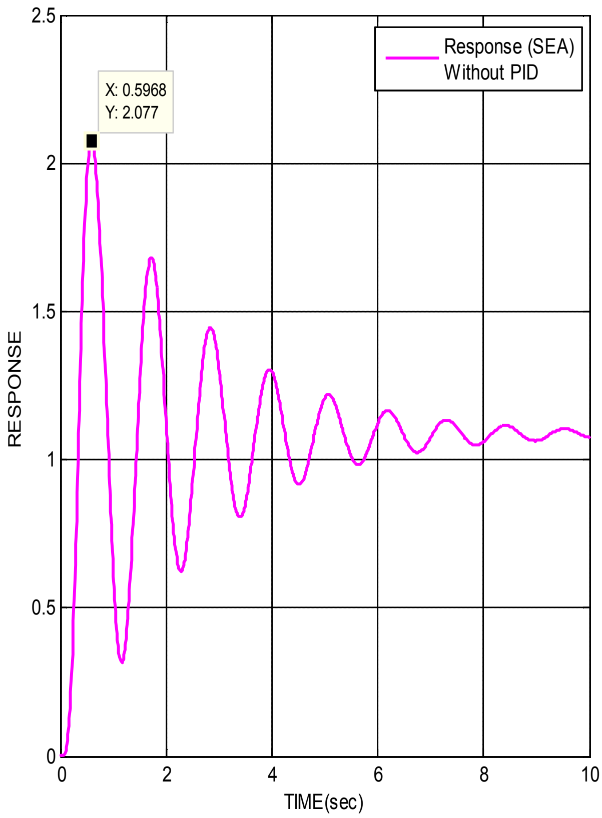

Fig. 12 Result Simulink of the (SEA) without PID Controller

From this figure, the value of the system response is more than the required value. But when PID controller used in the system the results show that there is a great improvement in the value and time of response. As shown in figure (13), there is only one oscillation before the (SEA) goes to the desired position, instead of five oscillation without the PID utilized. While the peak amplitude reduces to 1.03 at 1.1sec instead of 2.077 at 0.596 sec, the settling time was reduced by a third.

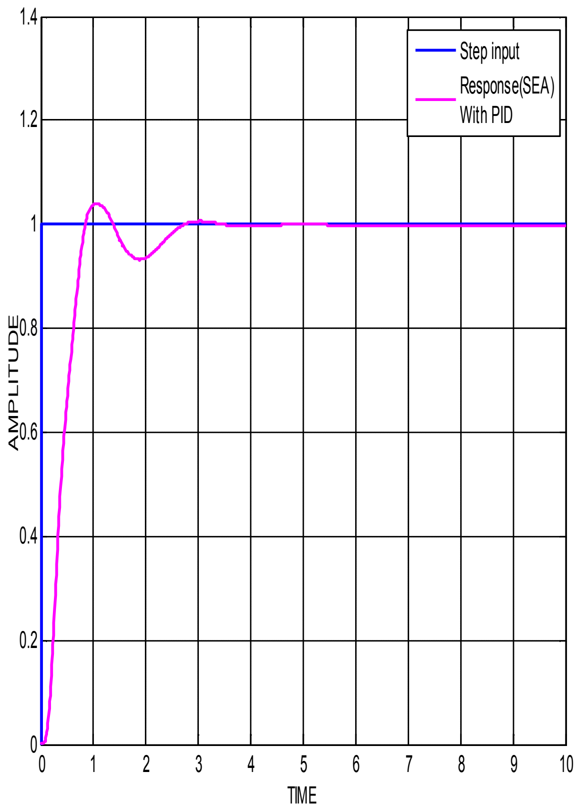

Fig. 13 Result of Simulink the Series Elastic Actuator (SEA) during 10 sec with PID.

After substituting the values of parameters, the dynamic characteristics of the DC motor are obtained. The transfer function of Series Elastic Actuator (SEA) system can be analyzed to obtain five poles as following:

$$G(s) = Tf = \frac{0.075}{0.00012S^5 + 0.039S^4 + 0.774S^3 + 23.77S^2 + 43.6S + 696.1}$$

Thus:

$$s_1 = -306$$
$$s_2 = -0.443 + 5.72i$$
$$s_3 = -0.443 - 5.72i$$
$$s_4 = -9.11 + 22.7i$$
$$s_5 = -9.11 - 22.7i$$

Figure (14) locates the roots (poles) on the left side of S-plane and this means that the system is stable and depends on the value of the gain which makes the system unstable or more stable. By drawing the path of the root locus, the value of the critical gain (kc) can be determined at the intersection with the imaginary axis, thus the critical gain is (kc = 2.6e4). When the gain is larger than 2.6e4, the system is unstable. While the system became stable when the gain is smaller than 2.6e4.

The obtained results can be combined as shown in table (1) in three cases:

1. When the gain is greater than (5.9e3). In this case, the system is unstable and both frequency and maximum overshoot are increasing uniformly. Here, the damping value is a negative value.
2. When the gain is equal to (5.9e3). The system is in critical case. Here, the value of the damping is equal to zero and the value of maximum overshoot is equal to 100%, while the frequency is 7.4 (rad/s).
3. When the gain is less than (5.9e3). The system is stable and the value of the damping is postive, while the maximum overshoot is less than 100% and the steady state error SSE decreases.

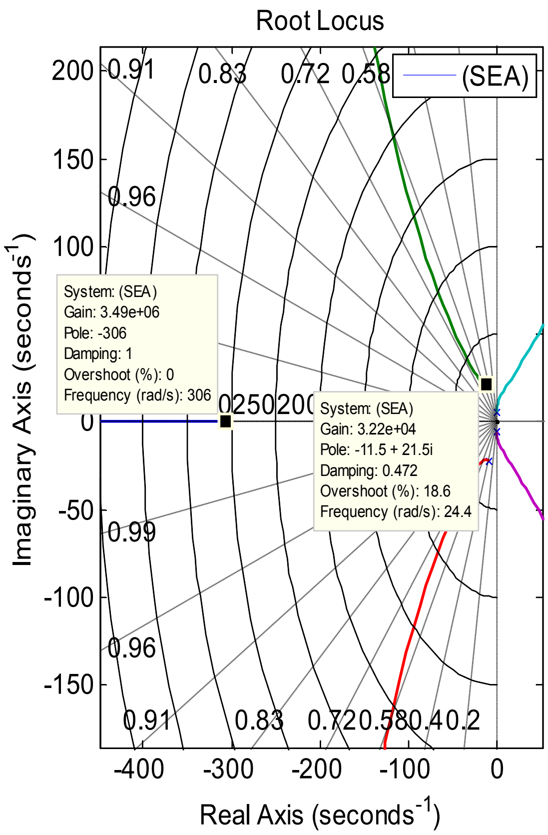

Fig. 14 Root Locus of Series Elastic Actuator (SEA)

From the analysis and study of the simulated results for (SEA), it has been observed that there is a change occurs to the system characteristics when PID controller is used. On this basis, the system characteristics must be studied in details. Therefore, PID controller is used to improve all results Controller parameters represent a tuning function for PID controller unit are illustrated in table (1).

Table. 1 Performance and Robustness after using PID Controller

Character -istic	DC Motor	(SEA)
K_P	0.06506	19538.8
K_I	0.00653	25686.5
K_D	0.0483	2679.99
Overshoot	10.6%	7.14%
peak	1.11	1.07
Rise time	0.707sec	0.525sec
Settling time	10.8 sec	2.59sec
Phase margin	60 deg at 1.84rad/s	60 deg at 2.53 rad/s
Closed-loop stability	stable	stable
Gain margin	41.4 dB at 28.4 rad/s	11.8 dB at 12.2rad/s

Conclusion

The main conclusions obtained from the present investigation are listed below:

1. Actual experimentation on Series Elastic Actuator (SEA) is expensive, time-consuming and needs a great effort. In other hand, the simulation using MATLAB Simulink is inexpensive and fast when used to investigate the (SEA) system components.
2. System impedance to surrounding force changes is good.
3. The error value of angular displacement and the settling time of the DC motor are 6.4 % and 10.8 sec respectively, while they decreased to 7.14 % and 2.59 sec when (PID) controller is used.
4. The response of the proposed passive system depends on both spring stiffness and damping coefficient, if they decreased then the response will improve for the proposed passive system.
5. The results improved significantly when PID controller used for Series Elastic Actuator (SEA) system. The maximum overshoot and settling time of the proposed (SEA) system are decreased to 7.14 % and 2.59 sec in case of position control.
6. It is observed that the accuracy of the results of this study had decreased when the frequency value increased.

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السيطرة الموضعية على سلسله المحرك المرن باستخدام برنامج ماتلاب سميولنك

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بغداد-العراق

الخلاصة:

تحليل الرياضي و المحاكاة لسلسلة المحرك المرن لغرض تحسين الخصائص الديناميكية للسيطرة على الازاحة وإمكانية استخدام اردوينو و المحاكاة في برنامج الماتلاب لغرض السيطرة على النظام. تبحث هذه الورقة في تصميم سلسلة المرن المحرك والنموذج المقترح لدرجة واحدة نشطة من الحرية (كتلة ونابض ومخمد) يركز على سلوك عابر للنظام. إنتاج استجابة عابرة سريعة لأمر الخطوة، والوصول الى حالة مستقرة، وتخفيض معدل الاهتزاز.لذا فإنه من المرغوب فيه أيضا جعل النظام أقل حساسية للاضطراب وقصر وقت التسوية.وللحصول على هذه الاهداف يتم توئمة النظام عن طريق استخدام وحدة التحكم والتي تتالف من (النسبي والمشتق والمتكامل). دراسة التحليل النظري لنظام التحكم لتحسين الأداء (سلسلة المحرك المرن) للمراقبة النشطة. وبناء جهاز اختبار للنظام المقترح سلسلة المحرك المرن . تم التحقق من صحة أداء هذا المفهوم بنجاح في التجارب على سلسلة اختبار المحرك المرن و اختبار للنظام النشط. وتظهر النتائج النظرية والتجريبية أن وحدة تحكم المستخدمة في التحكم حلقة مغلقة ردود الفعل أدى إلى تحسن كبير في النتائج وكذلك تقليل زمن الاستجابة للنظام. .حيث تم تقليل الحد الأقصى للتجاوز إلى (7.14٪) ويتم تقليل وقت الاستقرارإلى (2.59 ثانية) .

الكلمات المفتاحية: سلسلة المحرك المرن،وحدة التحكم بي اي دي ،سميولنك ماتلاب ،اردوينو