Al-Khwarizmi Engineering Journal, Vol. 18, No. 2, June, (2022)
P. P. 43- 54

Al-Khwarizmi Engineering Journal

Intelligent Tuning Control of two Link Flexible Manipulator with Piezoelectric Actuator

Marwah Abdulazeem Ali* **Ahmed Abdul Hussein Ali****

*,**Department of Mechanical Engineering/ University of Baghdad/ Baghdad/ Iraq*
*Email: m.sareaa1803m@coeng.uobaghdad.edu.iq
*Email: Ahmedrobot65@yahoo.com

(Received 25 March 2022; Accepted 16 June 2022)
https://doi.org/10.22153/kej.2022.06.001

Abstract

This paper represents an experimental study on the application of smart control represented by the use of the fuzzy logic controller. Two-link flexible manipulators that are used in airspace and military applications are made of flexible materials characterized by low frequency and damping ratio. To solve this problem, this paper proposes the use of smart materials (piezoelectric transducers), where each link is bonded with a pair of piezoelectric transducers that act as a sensor and another as an actuator. As the arm vibrates because of the movement generated by the motor, this voltage is controlled by a regulator inside the LABVIEW® 2020 software and sends the output control voltage to the piezoelectric actuator. Experimental results show that fuzzy logic control was efficient during high amplitude and led to pronounced results in suppressing vibrations within a short time. Fuzzy logic gives more flexibility to the designer and allows him to control the system through its simple implementation. This differs from classical control, which requires a mathematical model.

Keywords: *Two link flexible manipulator, active vibration control, smart structure, Fuzzy logic control.*

1. Introduction

Flexible manipulators that are used in numerous applications like industrial, aerospace, military, and the environment that are dangerous for humans to work in and are replaced by robots are made from flexible and thin materials, which have many advantages like low energy consumption, low weight, and high speed [1]. Although it has benefits, it also has negative characteristics, and those are vibrations. Because robots are limited by their dynamic behavior due to low frequency and low stiffness, these vibrations lead to problems between the high speed and the accuracy that's required. The two-link manipulator consists of two cantilever beams and two joints with a DC servo motor, where the flexible link is attached to rigid actuators, such as motors. Flexible materials with less damping and lighter weights are more susceptible to dynamic loads caused by environmental factors and human activity [2]. The stability of these flexible materials is proven by the kinetic force and the rotational load, which generate many separate vibrations, and the flexible link produces a large number of amplitudes through a continuously varying force in time. Vibrations can affect a variety of aspects, including sensitivity and accuracy [3]. Active vibration control proposes vibration mitigation and the generation of an opposing force equal to the action force that creates vibration, which has an effect on the system's stability and performance. There are numerous control algorithms, both classical and intelligent, that can cope with the vibration suppression of flexible structures; fuzzy logic control is used to control the system [4]. To eliminate additional noise from machinery, smart material piezoelectric (sensor/actuator) is used. It can generate an electrical signal when it is under mechanical stress, and this is called the sensor [5].

When used as an actuator, it produces an electrical signal to generate a mechanical stress opposite to the initial stress in order to obtain damping. This is called the actuator. The behavior of the piezo can be summarized in two ways: direct effect and reverse effect. These smart materials have active vibration control that is used to suppress vibration [6]. These manipulators are mathematically modeled using a variety of methods, including finite element methods (FE) and assumed mode methods (AMM), with flexible manipulators using the Lagrange equation and Euler's brnoilly to drive the equation of motion [5]. These structures with piezoelectric material besides control are called "smart structures." Research performed a lot of work on controlling the vibration of the manipulator. Luiz et al. [6] worked on the fuzzy logic controller to control the vibration on the steel cantilever beam using no mathematical model, just the identification of input-output and the rules of fuzzy logic. A fuzzy controller was developed for effective control performance on a piezo actuator. The experimental results suggest that the current control mechanism is effective. [7]. Kamel, et al. Analyzing the effects of various controllers on system performance using finite element analysis (FEA), works on vibration control using a new dynamic model. Three additional intelligent controller methods were examined to improve system performance. PID-AT (PID auto-tuning), PD, and STFC (self-tuning fuzzy controller). The system with STFC has the least overshoot, rise time, and improved performance because the rise time was so near to steady-state.

This paper presents an intelligent control strategy for regulating two links of a manipulator, which is modeled as two flexible cantilever beams contacted by two joints with a translation base (DC-servo motor). The contribution of this paper is to suppress the vibration in the two links of a flexible, smart robot. and intelligent tuning of the PZT sensor signal. To achieve this, an active vibration control process is applied. One of the active vibration control algorithms with five membership functions and 25 rules is selected for regulating the PZT sensor signal in the two beams. Experimental results indicate the satisfactory control performance and robustness of the adopted control schemes. The fuzzy logic controller cuts out a lot of steps and makes the control process easier to understand.

2. Mathmetical Modeling

A mathematical model of the structure is required for placing the piezoelectric. The Euler-Bernoulli beam theory, Piezoelectric theory, Dynamics theory, Control's State space theory, and functional analysis are all used to create the mathematical model [8].

To generate the dynamic equation of motion, all mathematical models are subjected to generalized global transformations, resulting in a state-space model of the plant that may be used for any type of controller design. The Finite Element Method (FEM) divides a flexible aluminum cantilever beam of sufficient size into four finite elements to gain the smart structure's final dynamic equation [9].

An external force operates on the two beams when the motor rotates at a specific angle. As illustrated in Fig.1, there is a transverse displacement u as well as bending moments M_1 and M_2 at node 1 (fixed end) and node 2 of the beam element, respectively. The deflection behavior of the flexible cantilever beam element is studied using the displacement function u (x, t).

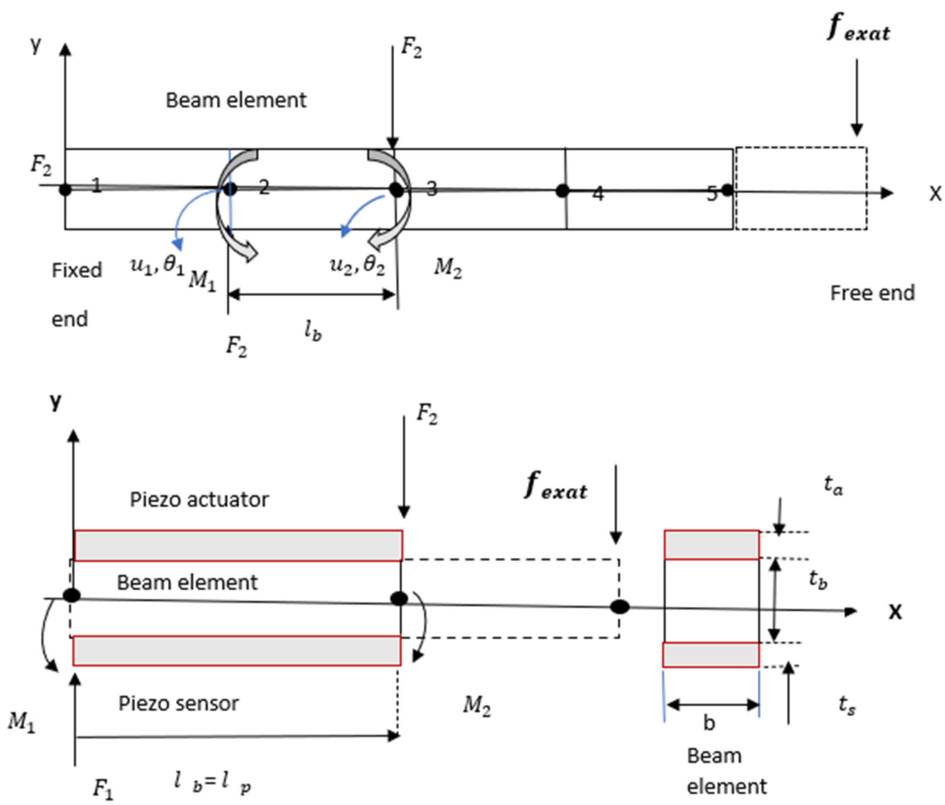


Fig. 1. Smart flexible beam bonded with piezoelectric as (sensor/actuator) divided into 4 finite element.

The dynamic equation of sensor output of the smart manipulator which is comprise regular beam element equation and piezoelectric beam element is given by [10]:

$$M\ddot{q} + C\dot{q} + kq = f_{ex} + f_{Ct} \quad \ldots(1)$$

$$y(t) = v_s(t) = p^T\dot{q} \quad \ldots(2)$$

Where, M and K, are the global mass and stiffness matrices of the smart beam, respectively, $\ddot{q}$ and q are the acceleration and displacement vectors, f_{ex} and f_{Ct} are the external force applied to the beam and the controlling force from the actuator, respectively.

Equation (3) is the state space model of the smart structure is developed for 2 vibratory modes (fundamental & 1st harmonic) and equation 4 is the output sensor [8,9].

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & I\\ M^{-1}k & -M^{-1}C\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix}0 & I\\ M^{-1}T^T h_1 & M^{-1}T^T h\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix} + \begin{bmatrix}0\\ M^{-1}T^T f\end{bmatrix} r(t) \quad \ldots(3)$$

And sensor output as [8,9]

$$\begin{bmatrix}y_1\\ y_2\end{bmatrix} = \begin{bmatrix}0 & p_1^T\\ 0 & p_1^T\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} \quad \ldots(4)$$

which is obtained in state space form as the final mathematical model given by

$$\dot{x}(t) = Ax(t) + Bu(t) + Er(t) \quad \ldots(5)$$

$$y_{(t)} = c^T x(t) + D\,u(t) \quad \ldots(6)$$

The two links considered as two smart cantilever beam divided into 4 finite element bonded with PZT.

3. Fuzzy Logic Control

For suppression of the vibration in the two-link flexible manipulator, fuzzy logic with different membership functions is used. It requires more design decisions than classical, model-based controllers. The fuzzy logic-based active vibration controller

Fuzzy logic control is made up of four steps: fuzzification, fuzzy rule, fuzzy inference engine, and defuzzifier [12].

Fig. 2 describes the four principal elements of fuzzy logic. The inclusion of the fuzzy logic controller inside the system is crucial, as it starts with the signal captured by the sensor and ends with the signals entering the piezoelectric actuator, as well as the type of system.

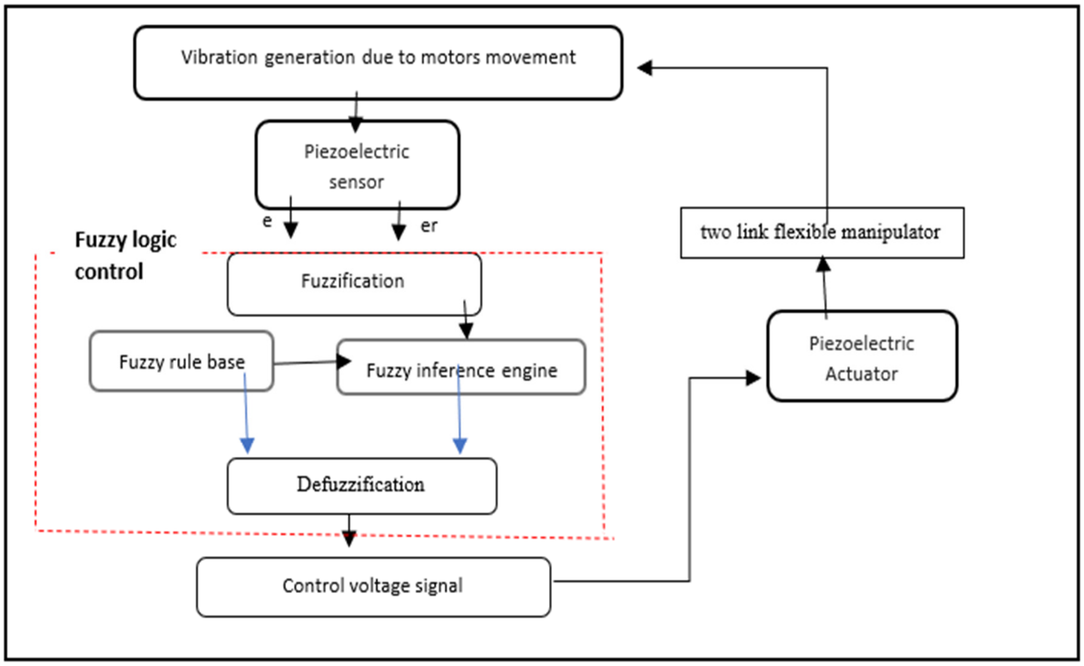


Fig. 2. Research method of the system comprises principle fuzzy controller.

3.1 Fuzzification

The interpretation interface of the input/output parameters is the initial step in creating a fuzzy controller. The vibration amplitude and change rate are represented by the input error (e) and the rate of change of error (er) in this investigation. The voltage signal and its derivative, which can be gotten by a PZT sensor. The output variable u is a voltage (control) signal that is transmitted to piezoelectric actuators through a voltage amplifier. The input domain and output domain are represented by five linguistic levels (NH, NS, ZE, PS, PH), which mean "negative high," "negative small," "zero," "positive small" and "positive high," respectively. The membership values range from (-5 to +5) In this study, triangular fuzzy membership functions were chosen.Figure 3 depicts the fuzzy control membership function [].

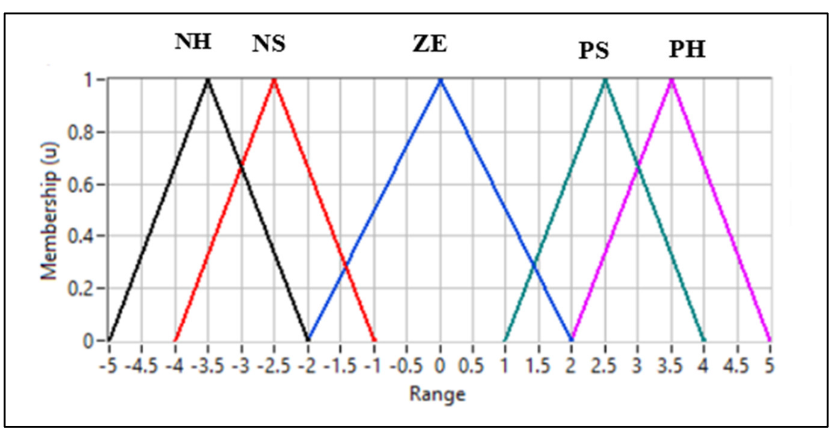


Fig. 3. membership function of the system control.

Selecting the range of membership depends on the design of the control system.

3.2. Fuzzy inference and fuzzy rules

The fuzzy controller's control rules are frequently based on experts' experiences and are expressed as IF-THEN rules that link input and output variables. The IF-THEN rule is as follows [14]:
IF e is NH and er, then u is PH

The fuzzy logic system's input and output variables are represented by e, er, and u (error, error change, and output) may reduce the number of control rules for the beam vibration control system using this strategy. The vibration control system is listed in Table 1. The first column, error e, and the first row, error rate er, describe the rule.

Table 1,
Fuzzy inference rules of the system control.

er **u** **e**	**NH**	**NS**	**ZE**	**PS**	**PB**
NH	PH	PH	PH	PS	ZE
NS	Ps	PS	PS	ZE	NS
ZE	ZE	PS	ZE	ZE	PS
PS	PS	ZE	NS	NS	PS
PH	ZE	NS	NS	NM	NS

3.3 Defuzzification

The step of converting the fuzzy inference result to numerical output and translating it to an actuator to damp the flexible beam where it bonded and get active control of the system.

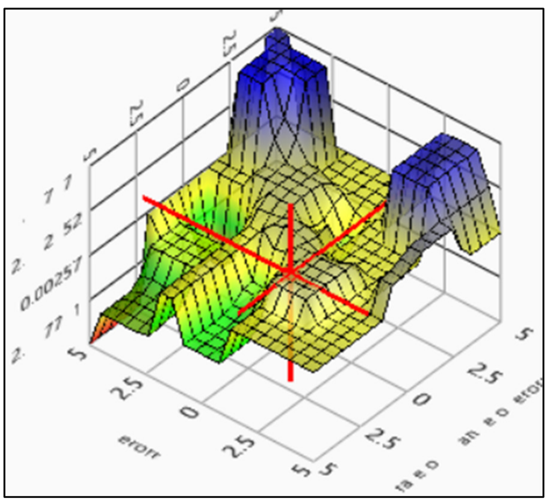


Fig. 4. Viewed surface of input/output relationship.

4. Experimental Setup

To suppress the vibrations that occur in the two-link manipulator and help to achieve stability in a short time. Fig.5 shows the process diagram for operating the system, starting with the electrical signals for the distortion being got from the piezoelectric sensor, which is then transferred to the data acquisition (DAQ), and then transferred to the LABVIEW program, which is installed on the computer. The whole circuit is regulated by the fuzzy controller within the LABVIEW program. The signal is transmitted and amplified by the amplifier and transmitted to the piezoelectric actuator, which generates a mechanical stress to control the vibration in the two-link flexible manipulator. The hardware used in conducting the test is shown in Fig. 6. It has an aluminum beam, a piezoelectric patch, a data acquisition NI USB 6353, an E-463 HVPZT amplifier, and a laptop with LABVIEW software to control the system.

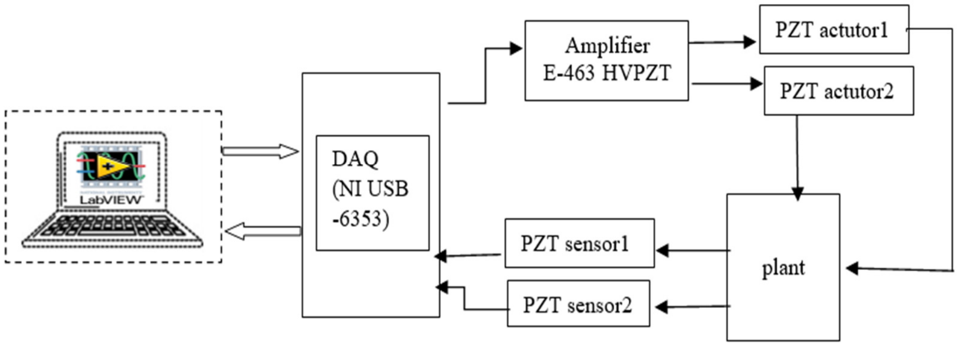


Fig. 5. The schematic diagram steps of experimental work.

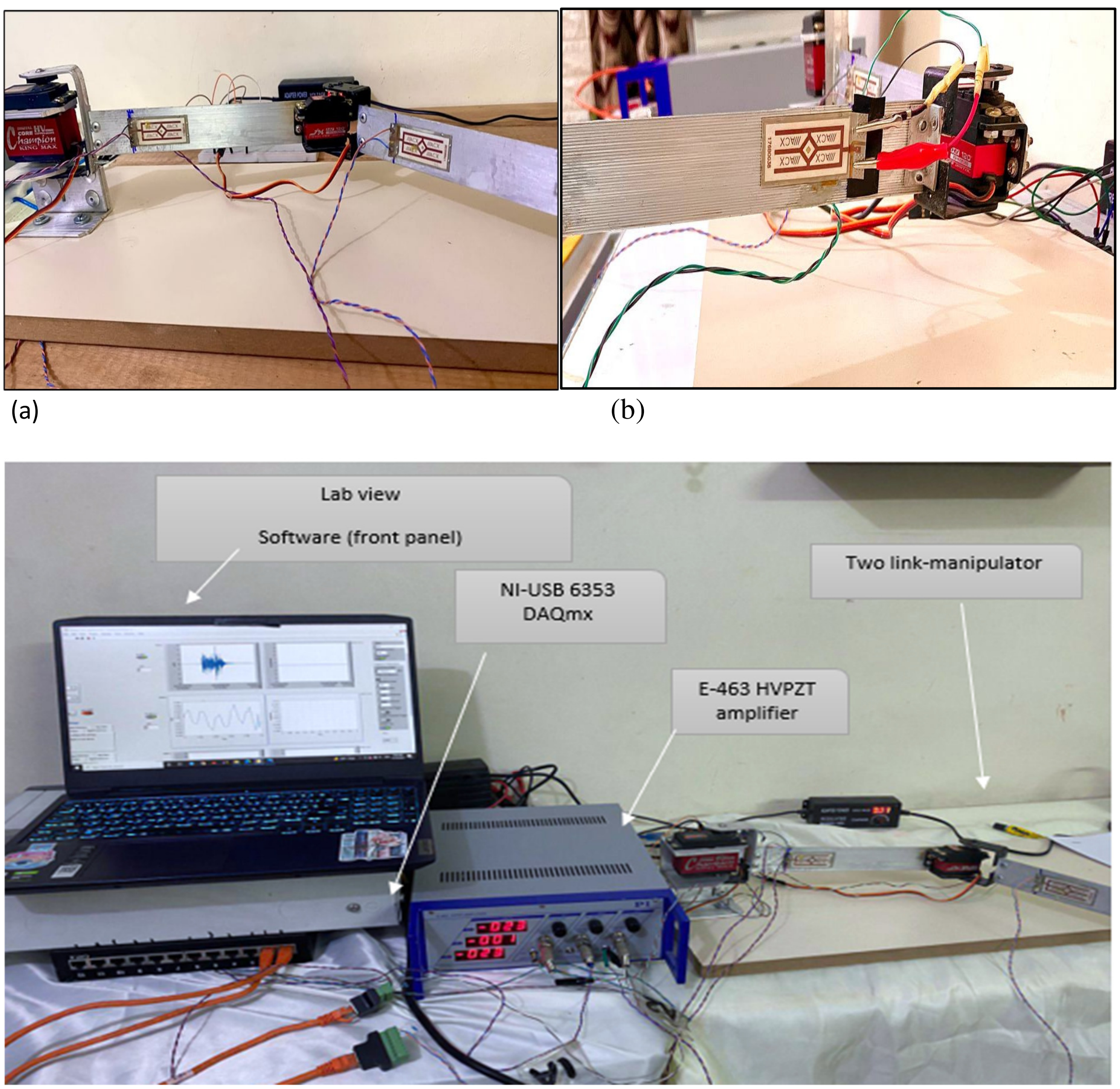


Fig. 6. Experimental system (a) two-link flexible manipulator,(b) the second link bonded with a piezoelectric actuator.

Table 2,
The flexible manipulator physical and geometrical characteristics, as well as the piezoelectric.

Physical Specification	Two link flexible manipulator	piezoelectric	Unit
Length	245	40	mm
Width	35	23.5	mm
Thickness	2	0.46	mm
Density	2810	7870	Kg/ m^3
Young modulus	71	50	Gpa
D_{31} (strain constant)	-	-320*10^{-12}	m/v
G_{31} (PZT stress constant)	-	-9.5*10^{-3}	m/v

Figure 6 shows the experimental setup it consists of the following parts: first, a two-link flexible manipulator; and second, the measuring and controller part.

The smart two-link flexible manipulator is made from two aluminum links. Each arm is connected with joints to facilitate movement, which is connected with a DC servo motor to get the movement of the system and control the vibrations deduced from the movement.

Two DC servo motors are used to move the flexible manipulator about the Z axis. The first is positional rotation, which contains strong metal gears that work at 8 volts and provide high torque of 50 kg [16]. The second motors also positionally rotate to provide 30kg of torque at 7 volts, working at a maximum angle rotation of 180 and changing speed according to the angle of rotation 45 degree applied with angular speed. [17] Two DC servo motors Two DC servo motors are driven by a microcontroller (Arduino mega 2560) programmed to the required movement. On its table are four piezoelectric transducers (type PPA1001-5H) with a full scale voltage of 120 volts and a mass of 8 g, as well as steel pads at the end for electrical terminals for energy harvesting and sensing applications [18]. The four piezoelectric bonded on each arm near the fixed end, two on each link, and one sensor and one actuator in one link, are bonded by special adhesive glue. piezoelectric bonded on the beam have two piezoelectric sensors connected with a resistor of 1 megohm to get a constant voltage of up to 10 and don't exceed it because of DAQ-mxUSB, a piezoelectric sensor used to sense the electrical voltage of the strain in the links. The electric voltage is the measurement of the amplitude. The NI DAQmx-6353USB includes a cable that connects to a laptop to acquire data from a piezo sensor and send it to the actuator after being controlled by the NI-LABVIEW® 2020 software. As shown in schematic diagram Fig.4, DAQ has analog input and output. The output control voltage will be amplified from (6) to 24 times by the (HVPZT-E463) high voltage piezo amplifier and reach 144 to drive the piezo electric actuator.

5. Results and Discussion.

The experiment has been done according to specific velocity and angular rotation to verify the validity of suppression vibration of the designed two-link manipulator and adopt fuzzy logic control. In the experiments, both the degree and angular rotation of the two DC-servo motors are (and =35 r/s, and =45 r/s) via Arduino. The ability to suppress vibration of the two-link manipulator is the basic concept in this system. The velocity and delay must be low because that may lead to the destruction of the two-link manipulator. The aim of the movement of the two motors is to get the excited vibration required to verify the active control in the two-link manipulators. Fig.7 shows that the maximum overshoot is 5.27v and the settling time is 14 s to be in a steady state for the first link and for the second link, as shown in fig.8, the greatest The maximum overshoot observed is 2 v, which is less than the electrical signal coming out of the first link because the motor that drives the first link has higher torque than the second. Fig. 9 shows the effectiveness of the fuzzy controller in reducing the electrical signal after applying the membership; it reached 0.3v, which is a very low value compared to 5.27v. Referring to this extent does not mean getting better damping and regulation, as in Fig.11, it was reduced to 0.19v. Figures 10 and 12 show an enlarged part of figures 9 and 11, respectively, which show the shape of the wave after the regulation, where there are very small waves that need some kind of control, like classical control (PI, PD, or PID) to keep their regulation.

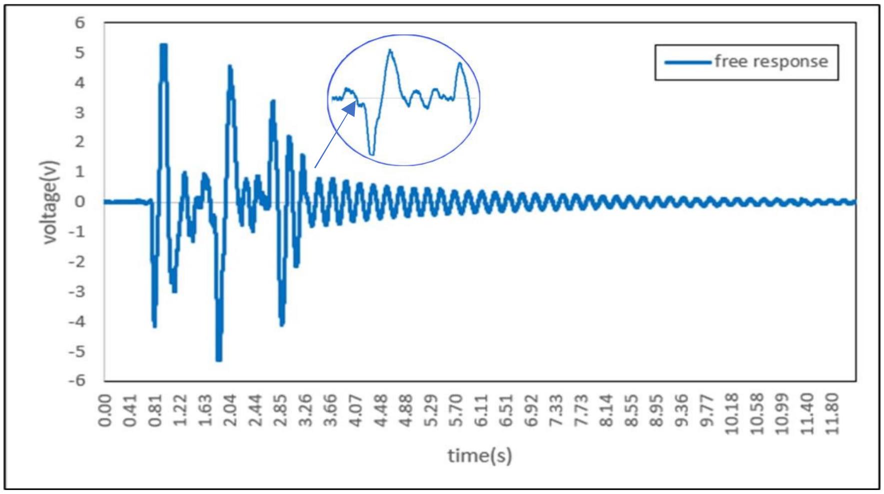


Fig. 7. Vibration Response of the First Link without active control FLC.

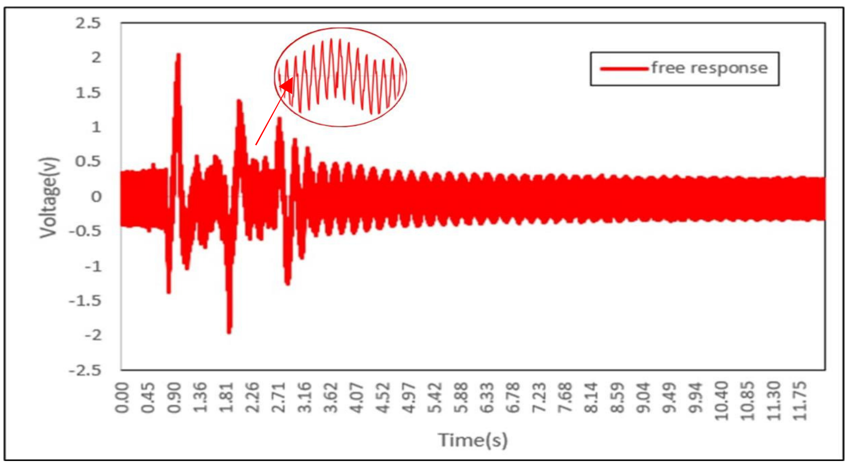


Fig. 8. Vibration Response of the Second Link without active control FLC.

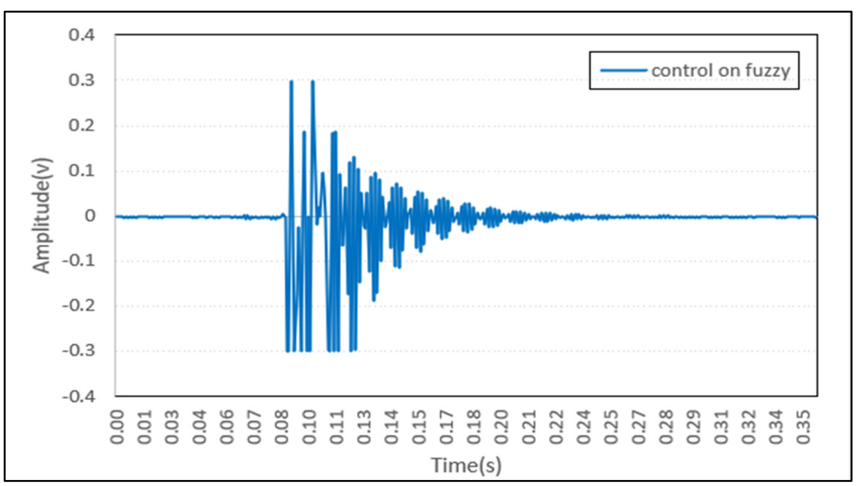


Fig. 9. Vibration Suppression and Time Response under FLC for the First Link.

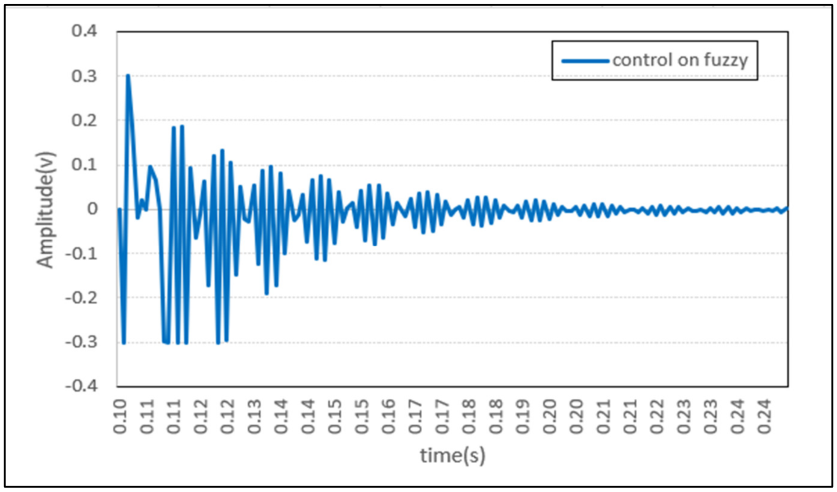


Fig. 10. Enlarged Shape of Vibration Suppression and Time Response of First Link under FLC.

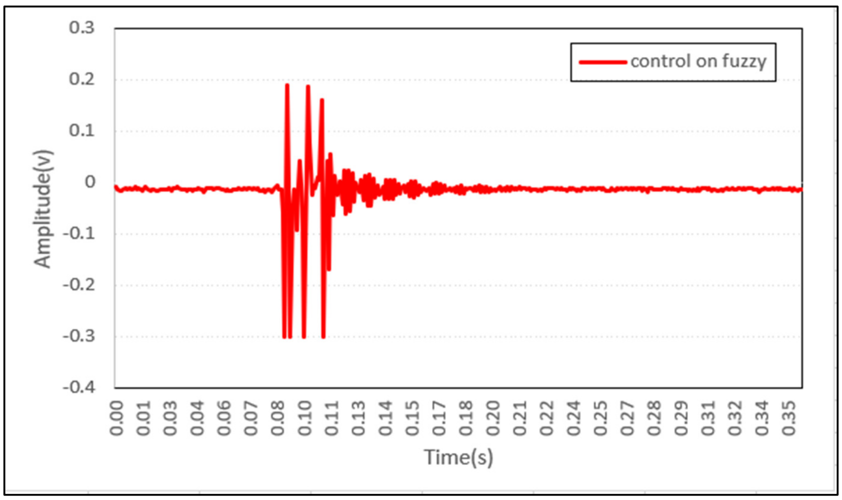


Fig. 11. Vibration Suppression and Time Response under FLC for Second Link.

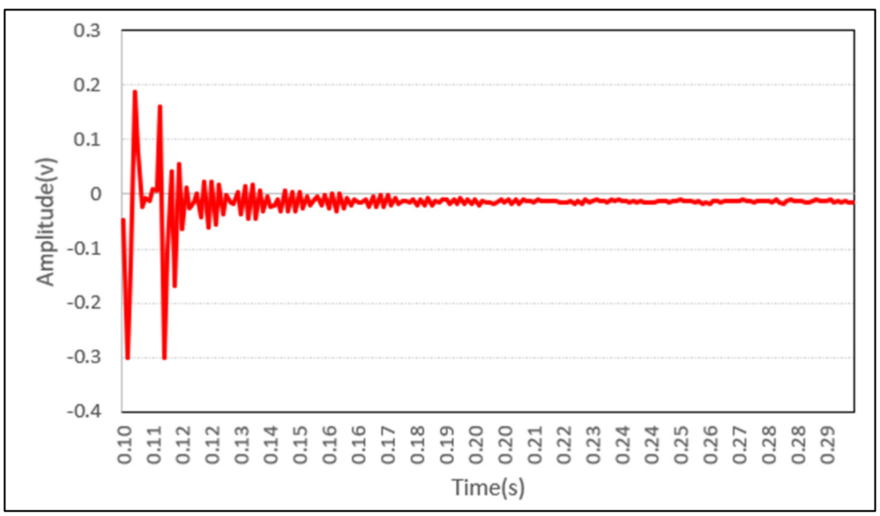
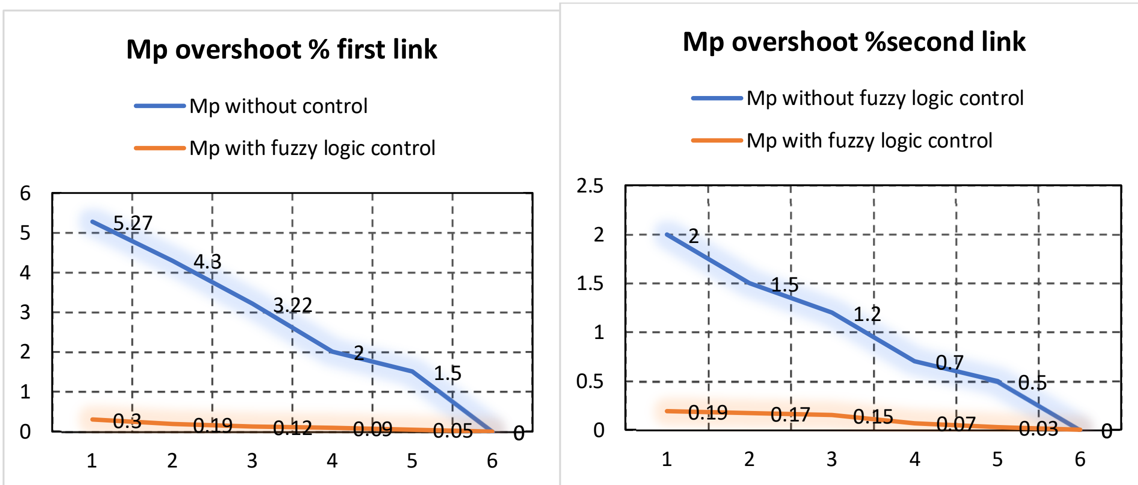


Fig. 12. Zoom in Vibration Suppression and Time Response of Second Link under FLC.



A- overshoot of vibration of first link. B- overshoot of vibration of second link.

Fig. 13. Comparisons of maximum overshoot of the two links with and without fuzzy logic control.

The maximum overshoot of the system was reduced after applying fuzzy logic control in the two beams, as shown in fig.13, which means the system's noise was reduced, and thus the vibration was reduced.

6. Conclusions

An intelligent control represented by the fuzzy logic controller has been used to improve the control of a two-link manipulator operated by DC servo motors using the built-in experimental apparatus and to control the vibrations that occur in it. Piezoelectric materials are used in the performance and to control the voltage coming out of the sensitive piezoelectric material by the fuzzy. The experimental results taken from the piezoelectric sensor of the two-link manipulator showed that fuzzy logic has a high effectiveness in suppressing large amplitudes. The damping occurs at nearly 40–35% in the smart two-link manipulator. The disturbance's robustness has also been addressed.

7. References

[1] Lu, S. F., Jiang, Y., Zhang, W., & Song, X. J, " Vibration suppression of cantilevered piezoelectric laminated composite rectangular plate subjected to aerodynamic force in the hygrothermal environment" European Journal of Mechanics, A/Solids, 83.2020.

[2] Djojodihardjo, H., Jafari, M., Wiriadidjaja, S., & Ahmad, K. A," Active Vibration Suppression of an elastic piezoelectric sensor and actuator fitted cantilevered beam configurations as a generic smart composite structure" Composite Structures, 132, 848–863. https://doi.org/10.1016/j.compstruct.06.054.2015.

[3] Lin, C. Y., & Jheng, H. W, "Active vibration suppression of a motor-driven piezoelectric smart structure using adaptive fuzzy sliding mode control and repetitive control" Applied Sciences (Switzerland), *7*(3).2017.

[4] Qiu, Z. cheng, Li, C., & Zhang, X. min." Experimental study on active vibration control for a kind of two-link flexible manipulator" Mechanical Systems and Signal Processing, 118, 623–644. https://doi.org/10.1016/j.ymssp.09.001.2019.

[5] Lu, E., Li, W., Yang, X., Wang, Y., & Liu, Y. "Optimal placement and active vibration control for piezoelectric smart flexible manipulators using modal H2 norm" Journal of Intelligent Material Systems and Structures, 29(11).2018.

[6] Lochan, K., Roy, B. K., & Subudhi, B." A review on two-link flexible manipulators" In Annual Reviews in Control (Vol. 42, pp. 346–367). Elsevier Ltd.2018.

[7] Kamel, M. A., Ibrahim, K., & El-Makarem Ahmed, A," Vibration control of smart cantilever beam using finite element method" Alexandria Engineering Journal, *58*(2), 591–601.2019.

[8] Kusagur, S. M., Arunkumar, G., & Manjunath, T. C. "Modelling of smart intelligent materials with PZT & PVDF sensors/actuators to control the active vibrations of flexible aluminum mechanical cantilever beams using proportional integral derivative (PID) techniques"Materials Today: Proceedings, 37(Part 2), 2075–2082. https://doi.org/10.1016/j.matpr.2020.07.507.2 020.

[9] Thoma, M., & Morari, · M. (n.d.)." Lecture Notes in Control and Information Sciences "350.2010.

[10] dynstab, & ThePirateBay. (n.d.), "Mechanical Vibrations T H E O R Y A N D A P P L I C A T I O N S".2012.

[11] [mhsin N. Hamzah, Shibly Ahmed AlSamarraie, Imad Abdulhussein Abdulsahib.," Sliding Mode Vibration Suppression Control Design for a Smart Beam ", Journal of Engineering, 2016.

[12] Xu, S., Sun, G., & Sun, W. (2017). Fuzzy logic-based fault-tolerant attitude control for nonlinear flexible spacecraft with sampled-data input. Journal of the Franklin Institute, 354(5), 2125–2156.

[13] Wei, J. J., Qiu, Z. C., Han, J. da, & Wang, Y. C."Experimental comparison research on active vibration control for flexible piezoelectric manipulator using fuzzy controller". Journal of Intelligent and Robotic Systems: Theory and Applications, 59(1), 31–56.2010.

[14] Ali, A. A., Lateef, R. A. R., & Saeed, M. W. " Intelligent tuning of vibration mitigation process for single link manipulator using fuzzy logic" Engineering Science and Technology, an International Journal, 20(4).2017.

[15] "datasheet of 50kg. cm Metal Gear Servo Motor Waterproof ", china,2020. https://www.uruktech.com/product/50kg-cm-servo-motor.

[16] "datasheet of 30kg. cm Metal Gear Servo Motor Waterproof ", china,2020. https://www.uruktech.com/product/30kg-servo-motor/

[17] National Instrument, "datasheet of PI Physik Instrumente E-463 HVPZT - Amplifier 3-Channel Piezo". USA .2019.

[18] PPA-1001," Datasheet, MIDE CO.Ltd"., PPA-series ,USA,2019.

ضبط الذكي للتحكم في وصلة مناور مرن مع مشغل كهروظغطي

مروة عبد العظيم علي*   احمد عبد الحسين علي**

*، **قسم الهندسة الميكانيكية/ كلية الهندسة/ جامعة بغداد/ العراق

*البريد الالكتروني: m.sareaa1803m@coeng.uobaghdad.edu.iq

**البريد الالكتروني: Ahmedrobot65@yahoo.com

الخلاصة

يمثل هذا البحث دراسة تجريبية على تطبيق التحكم الذكي المتمثل في استخدام متحكم المنطق الضبابي. مناور مرن ثنائي الوصلة يستخدم في المجال الجوي والتطبيقات العسكرية، وهو مصنوع من مواد مرنة تتميز بالتردد المنخفض ونسبة التخميد. لحل هذه المشكلة، تقترح هذه الورقة استخدام مواد ذكية (محولات طاقة كهرضغطية) ، حيث يتم ربط كل وصلة بزوج من محولات الطاقة الكهروضغطية التي تعمل كمستشعر وآخر كمشغل. عندما يهتز الذراع بسبب الحركة التي يولدها المحرك، يتم التحكم في هذا الجهد بواسطة منظم داخل برنامج LABVIEW® 2020ويرسل جهد التحكم في الخرج إلى المشغل الكهرواجهادي. تظهر النتائج التجريبية أن التحكم المنطقي الضبابي كان فعالاً أثناء السعة العالية وأدى إلى نتائج واضحة في قمع الاهتزازات في غضون فترة زمنية قصيرة. يمنح المنطق الضبابي مزيدًا من المرونة للمصمم ويسمح له بالتحكم في النظام من خلال تنفيذه البسيط. هذا يختلف عن التحكم الكلاسيكي الذي يتطلب نموذجًا رياضيًا.