Active Vibration Control for Two-Link Flexible Piezoelectric Manipulator Using a fuzzy Logic Controller

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ABSTRACT

This paper represents an experimental study on the application of smart control represented by the use of the fuzzy logic controller. For a two-link flexible manipulator that is used in airspace and military applications, which is made of flexible materials characterized by low frequency and damping ratio. This problem is solved by smart materials (piezoelectric transducers), where each link is attached to a pair of piezoelectric transducers that act as a sensor and another as an actuator. As the arm vibrates due to the movement generated by the motor, this voltage is controlled by a regulator inside the LABVIEW® 2020 program software and sends the output control voltage to the actuator. When experimental results were recorded, it was noted that fuzzy logic control was very dominant during high amplitude and led to pronounced results in suppressing vibrations within a very short time of 0.31 seconds for the first link and 0.24 seconds for the second link.

Fuzzy logic gives more flexibility to the designer and allows him to control the system through its simple implementation. This is different from classical control, which requires a mathematical model.

KEYWORDS : Two link flexible manipulator, active vibration control, smart structure, Fuzzy logic control, Labview.

1-Introduction.

With the development of space structures during the modern era and the difficulty and cost of sending heavy materials into space, As a result, engineers used flexible light materials in manipulators, robot arms, spaceships, and aircraft for aerospace applications[1]. The two-link manipulator consists of two cantilever beams and two joints with a DC servo motor, where the flexible link that is attached to rigid actuators such as motors is characterized by speed and low energy consumption. Flexible materials with less damping and lighter weights are more susceptible to dynamic loads caused by environmental factors and human activity [2].

Despite the many advantages of light flexible material, vibration is the greatest disadvantage due to its low stiffness. [4]The stability of these flexible materials is proven by the kinetic force and the rotational load, which generate a large number of separate vibrations, and the flexible link produces a large number of amplitudes through a continuous varying force in time**.** Vibrations can affect a variety of aspects, including sensitivity and accuracy[3]. To eliminate additional noise for machinery, smart material piezoelectric (sensor/actuator) is used. It has the ability to 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:1-Direct effect 2-coverse effect. These smart materials have active vibration control that is used to suppress vibration. [6]

There are numerous control techniques like the classical method and the modern method, both used with smart material (PZT) to reduce vibration. In this work, intelligent control (fuzzy logic control) is easy and good for control with structure. It is hard to formalize a mathematical model. Fuzzy doesn’t need a mathematical equation. To design PZT smart structures for active vibration control, both structural dynamics and control theory need to be considered[7].

In this work, a fuzzy logic controller will be built inside the LABVIEW® 2020 program in order to achieve intelligent control of the Two link manipulator and suppress vibrations in the arms and contribute to the work of the fuzzy logic controller will shorten many steps and reduce the complexity of the control process.

2.Mathmetical Modeling.

To begin controlling any dynamical system, whether utilizing software or hardware, a mathematical model of the plant is required. 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].

1-modelling of regular beam element 2- modelling of piezoelectric (sensor/actuator) element 3- modelling of pzt beam element

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 utilized for any type of controller design. The Finite Element Method (FEM) divides a flexible aluminum cantilever beam of sufficient size into four finite elements. in order to acquire the smart structure's final dynamic equation [10].

The dynamic equation of sensor output of the smart manipulator which is consist of regular beam element equation and pzt beam element and is given by

$$M\ddot{q} + C\dot{q} + kq = f_{ex} + f_{ct} \qquad and \qquad y(t) = v_s(t) = p^T\dot{q}$$

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, $fext$ and $fctrl$ are the external force applied to the beam and the controlling force from the actuator, respectively.

Finally, the state space model of the smart structure is developed for 2 vibratory modes (fundamental & 1st harmonic) as[8,9]

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

And sensor output as [8,9]

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 & p_1^T \\ 0 & p_1^T \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$,which is obtained in state space form as the final mathematical model given by

$$\dot{x}(t) = Ax(t) + Bu(t) + Er(t) \, , y_{(t)} = c^T x(t) + D\, u(t)$$

The system matrix, input matrix, output matrix, transmission matrix, and external load matrix are the parameters A, B, C, D, and E, respectively. Take note of the matrices' dimensions, which are the same as the dimensions of the matrices. As two modes of vibration are being used, the system matrix will be (4*4) consider.

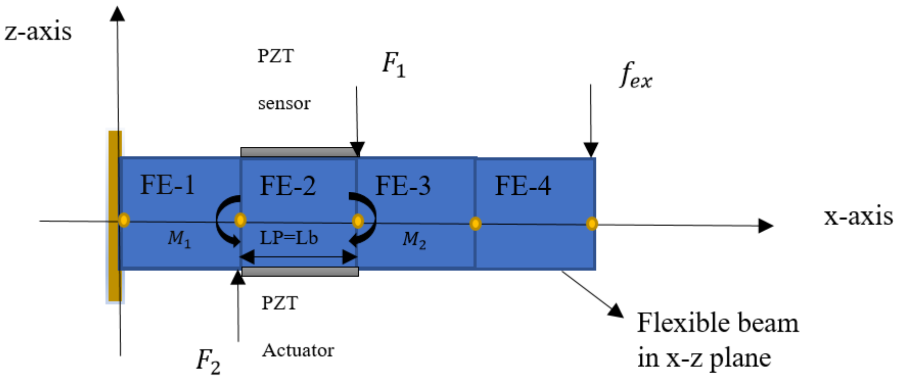


Fig.1 smart flexible beam bonded with piezoelectric as (sensor/actuator) divided into 4 finite element.

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

3- Active vibration control based on fuzzy logic.

Active vibration control proposes vibration mitigation and 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 used to control the system.

3-1 Fuzzy Logic Control.

For suppression the vibration in the two link flexible manipulator, fuzzy logic with different membership function is designed to suppress the low tip displacement(amplitude) vibration near equilibrium and reach stability fast (fast response). it requires more design decisions than classical, model based controllers. The fuzzy logic based active vibration controller was designed for the electric voltage from the sensor to actuator only.

Fuzzy logic control consist of four step : (fuzzification ,fuzzy rule ,fuzzy inference engine ,defuzzifier) [12].

Fig.1 describe the four principal element of fuzzy logic. by the step of fuzzy which it’s the key of the principle of fuzzy logic the intelligent control of the two link flexible manipulator designed.

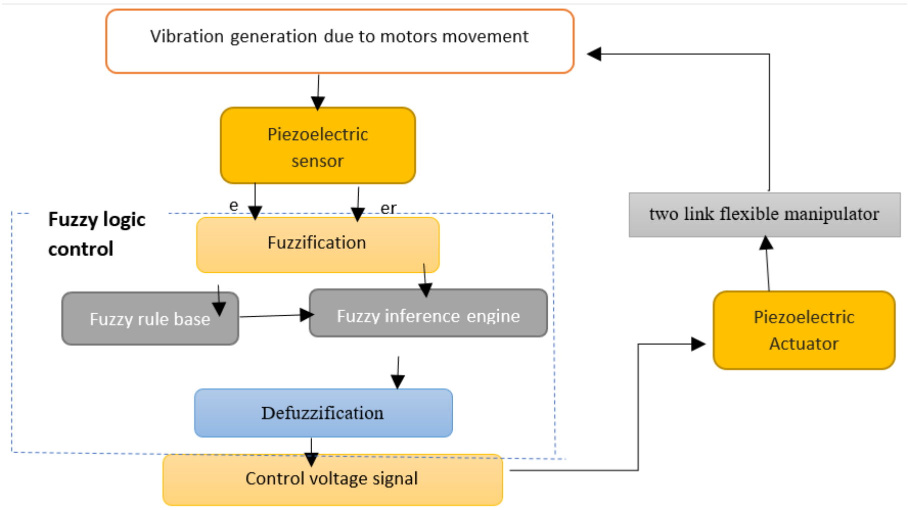


Fig.2 research methodology of the system consist of principle fuzzy controller.

3.1.1 fuzzification.

The first step in building fuzzy logic to control the system is fuzzification. It transposes the value from a crisp number to a fuzzy number for more accuracy.

Fuzzification refers to identifying the input and output parameters. The input will be error (e), sensor input voltage, which is the strain in the vibrating point (amplitude), and error rate (er).The output will be the control signal (u) that drives the piezoelectric actuator after being amplified by the piezo amplifier.

To get a better performance control system, the membership function will be divided into seven triangular memberships and seven linguistic terms **(NH, NM, NS, O, PS, PN, PH).** which means "negative high," "negative medium," "negative small," "zero, "positive small," "positive medium," and "positive high," respectively. The LABVIEW® 2020 software is used for all design and control[12].

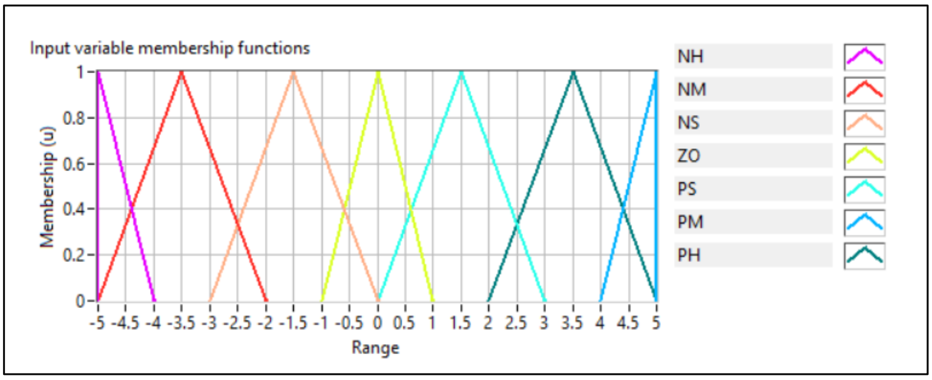


Fig.3: (membership function of the system control).

Selecting the range of membership depend on the maximum and minimum voltage of the block diagram of the control system.

3.1.2. fuzzy inference and fuzzy rules.

Fuzzy rule is the heart of the fuzzy logic it experts the experiences of the designer to the system, usually based on the laterial knowledge to the system must be control .

Its in the form of IF-THEN for example[13].

Rule : IF e is positive high "**NH**" and (er) "**NH**" then u is "**PH**"

Table 1. fuzzy inference rules of the system control.

er u e	NH	NM	NS	O	PS	PM	PB
NH	PH	PH	PH	PH	PM	O	O
NM	PH	PH	PH	PH	PM	O	O
NS	PM	PM	PM	PS	O	NS	NS
O	PM	PM	PS	O	O	PS	PS
PS	PS	PS	O	NS	NS	PS	PS
PM	O	O	NS	NM	NS	NS	NS
PH	O	O	NS	NM	NM	NS	NS

By this approach the rules of fuzzy logic infer to 49 for the two link vibration control system it listed in the Table 1 the first column error e and first row the error rate er describe the rule.

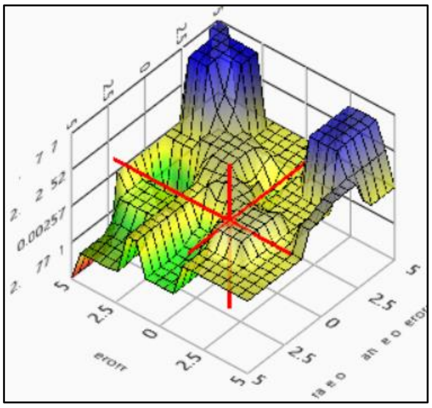


Fig.4 viewer surface of input/output relation ship.

3.1.3 Defuzzification.

The step to convert the fuzzy inference result to numerical output and translates it to actuator to damped the flexible Beam where it bonded and get active control to the system[13].

4. Experimental setup.

In order to show improvement in the performance of the system under intelligent control, experimental setups are created to achieve practical results.

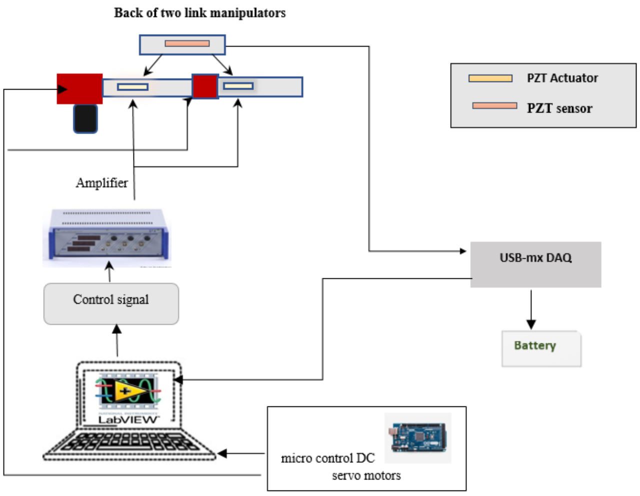


Fig.5 the schematic diagram steps of experimental work.

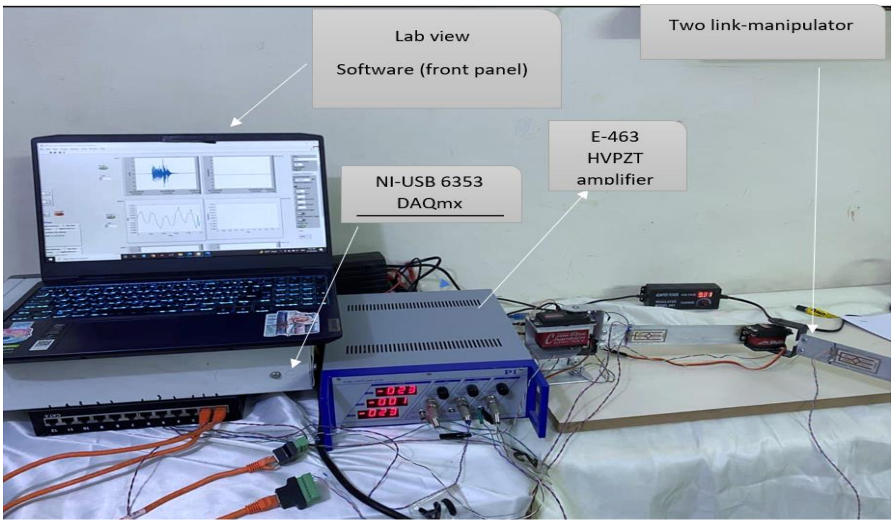


Fig. 6 Experimental system.

Table 2 The flexible cantilever beam's 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

In **Fig. 5** of the hardware of experimental setup was dedicated for vibration suppression. The hardware of Experimental setup consist of the main following parts:1-Two link flexible manipulator 2-Measuring and controller part.

The smart two link flexible manipulator made from two Aluminum links . Each arm is connected with joints to facilitate movement, which in turn is connected with DC servo motor in order to obtain the movement of the system and control the vibrations deduced from the movement.

Two DC servo motor used to movement the flexible manipulator about the Z axis perpendiculsar to the paper,the first is postional rotation contains strong metal gears works at 8 volts and provide high torque 50kg[14]. the second motors also postional rotation provide torque 30kg at 7 volts ,the two works at Maximum angel rotation 180 and speed changed according to the angle of rotation in this work 90 angle applied with anguler speed ,Two DC servo motors[14] programmed by microcontroller (Arduino mega 2560) to requred movement. Four piezoelectric transduser(type ppa 1001-5H) with full scale voltage 120 volts and mass 8 g with steel pads at the end for electrical terminals its sutible for energy harvesting and sensing application[15] . the four piezoelectric bonded on each arms near fixed end two on each link and in one link one is sensor and other actuator its bonded by special adhesive glue theses piezoelectric bonded on the beam ,two piezoelectric sensor connected with resistor 1 megaohm in order to obtain a constant voltage of up to 10 and doesn't exceed it due to DAQ-mxUSB, piezo sensor used to sensing the electrical voltage of the strain in the links. The electric voltage is the measurment of the amplitude . NI DAQmx-6353USB consist of cable connected to the laptop to get data equstion came from piezo sensor and send it to actuator after controllig byNI- LABVIEW® 2020 softwere , DAQ have analoge input and analoge output as shown in schimetc digram fig.4 . The output control voltage will amplifying it from ($\mp$6) to 24 time by (HVPZT-E463) high voltage piezo amplifier and reaches to $\pm$144 in order to drive piezo electric actuator

5. Experimental 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 adopted fuzzy logic control (2019). One set of vibration control was conducted. In the experiments, Through Arduino, the selected of both two DC-servo motor movements (degree angular rotation), which the degree of rotation as, 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 manipulator by Labview®2020.

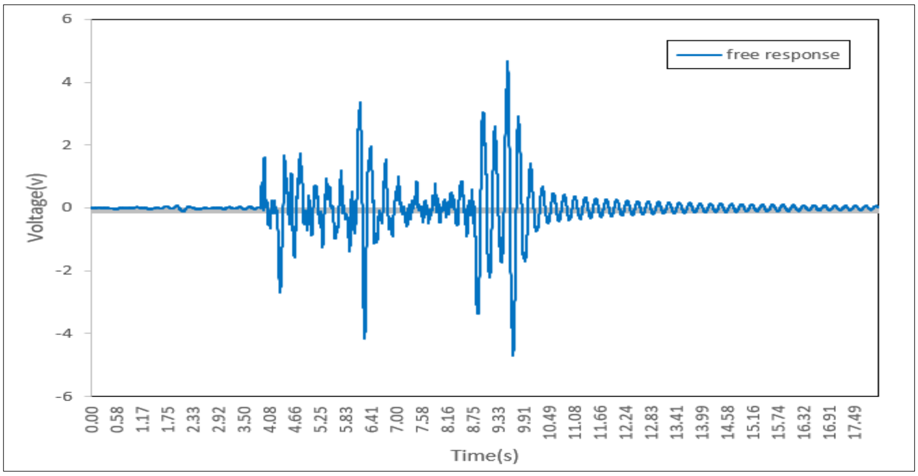


Fig.7 Experimentally measured vibration responses for first link without Fuzzy logic control (FLC).

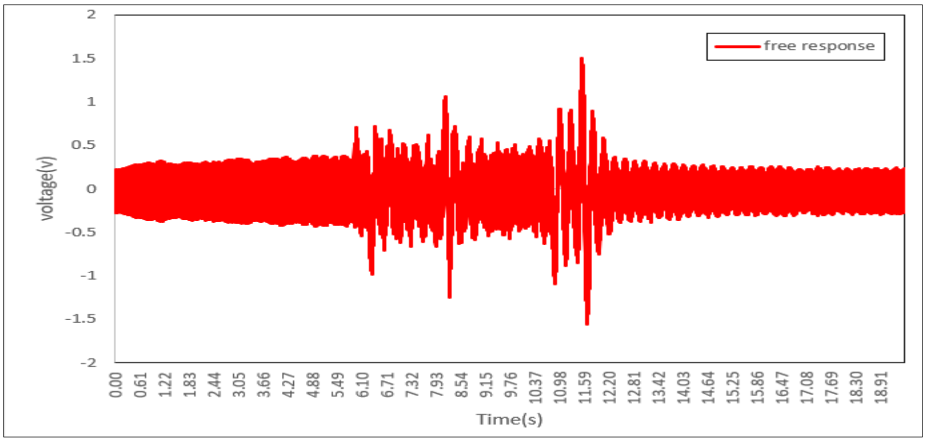
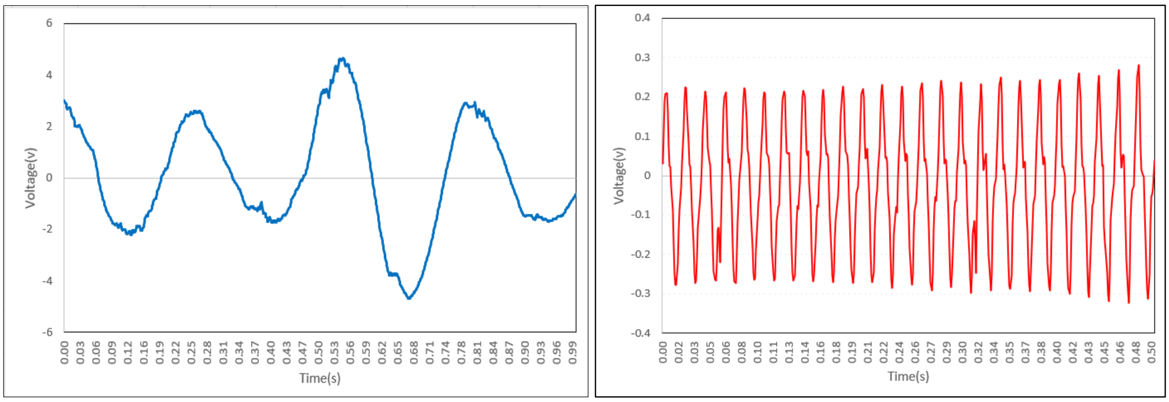


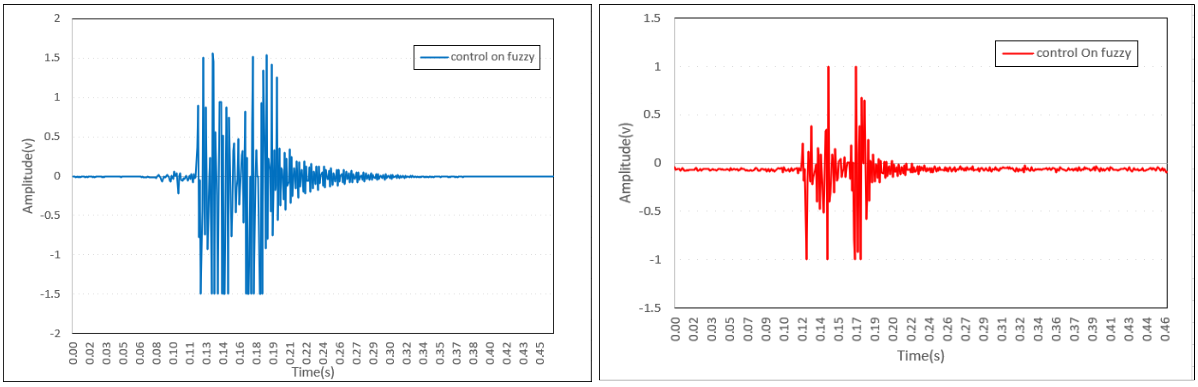
Fig.8 Experimentally measured vibration responses for second link without Fuzzy logic control (FLC).



b- Free response First link. a- Free response second link.

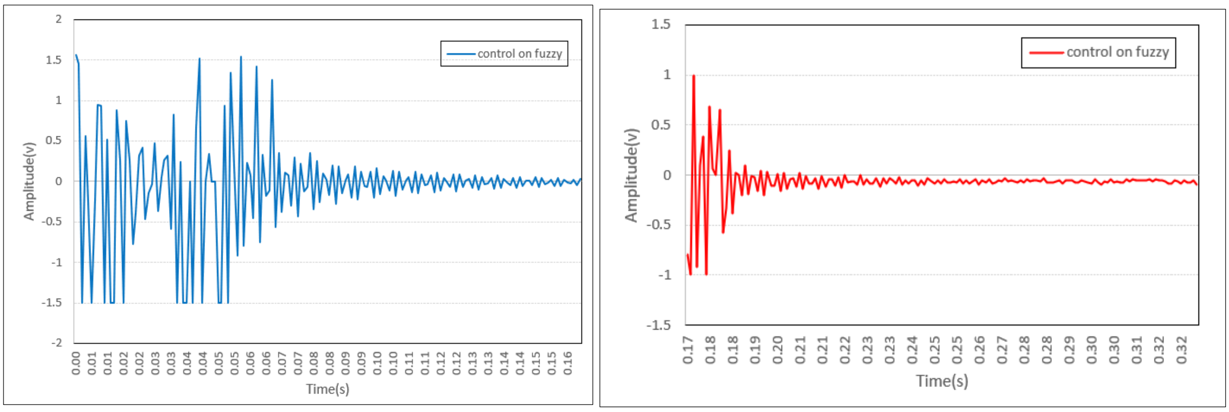
Fig.9 zoom in Time domain and vibration response for the two link manipulator.

Fig.7 shows the maximum overshoot is 4.5v and settling time is 14s to be in steady state for first link and For second link as shown in **fig.8** the greatest Maximum overshoot observing is 1.5 v which is less than the amplitude coming out of the first link because the motor which drive the first link has high torque than the second and the time response is15.6



a- First link under fuzzy logic. b- second link under fuzzy logic.

Fig.10.Time response and vibration suppression of the two link under fuzzy logic control.



a- Zoom First link under fuzzy logic. b- zoom second link under fuzzy logic.

Fig.11. zoom in Time response and vibration suppression of the two link under fuzzy logic control.

From fig (11) a and b of the response for first and second link the settling time and maximum overshoot decrease to reach the stability of the system . As the settling time decrease for first link is 0.14s for the first link and 0.22s for the second link.

6. Conclusions

In order to show an improvement in the performance of the system consisting of a two-link flexible manipulator operated by DC servo motors, utilizing the built-in experimental apparatus and to control the vibrations that occur in it, an intelligent control represented by the fuzzy logic controller had been used, piezoelectric materials were used in the performance and to control the voltage coming out of the sensitive piezoelectric material by means of the fuzzy. The experimental results taken from the piezoelectric sensor of the two-link manipulator showed that Fuzzy logic has a high effective in suppressing large amplitudes, The damping occur, nearly 40- 35% in the smart two-link manipulator. The disturbance's robustness has also been addressed.

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