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Experimental Validation of Hybrid Polymer Composite Material Robotic Single Link Flexible Manipulator

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Abstract*: The prime aim of this research is to conduct an experimental validation for the assessment of behaviour of a hybrid composite material. The hybrid lightweight composite material is used as a robotic link for replacement of rigid and giant manipulators. The combination of fibre material methodically processed and technically merged with epoxy, resulting in hybrid composite material which is used as robotic link movement application and experimentally validated with respect to its functional behavior and cost-effectiveness. In this experimental investigation, composite material is taken as a flexible link for vibration amplitude control analysis and flexible deflection determination using modern control system with various joint stiffness coefficient. The numerical evaluations are conducted for lightweight composite material as an alternate of rigid and solid link. The modelling of composite flexible link is carried out for precision and accuracy on the basis of Lagrange's equations of motion. The vibration investigation of the system is carried out and reduction of vibration is evaluated using model-based controller in the experiment.

Keywords: Motor servo MG995, terminal board, power module, accelerometer, strain guage, flexible link.

I. INTRODUCTION

A polymer composite robotic single arm is taken for the experimental study. The photographic experimental setup diagram shown in Fig.1. This experiment is designed to validate the performance behaviour of the composite material single link manipulator subjected to both link and joint flexibility. This model is based on modern controller implementation. This modern type controller is technologically advanced for path tracking and tip deflection calculation for accuracy. The accuracy of the robotic manipulator is the closeness of robot link position to its actual value [1].The experimental arrangement consists of Tower Pro MG 995 Digi High Speed rotary servo motor, Arduino Uno, Arduino Mega printed board, general power module, composite one arm with required accelerometer for vibration mode parameter measurement and strain guage are connected and the experimental setup as shown in the figure. In the clamped end side of a flexible link, a strain guage is attached. This strain guage is used to measure the tip flexible deflection. This experimental arrangement with strain guage setup shown in Fig.2. The Tower Pro MG 995 Digi high speed DC motor, consist of planetary gearbox internally. The internal planetary gear arrangement is engaged with gear attached outside. The entire arrangement of DC servo motor shaft, inside gear portion, and outside gear arrangement are enclosed in a casing. This arrangement introduce flexibility at the joint.

The joint flexibility in the system is different. It was found in the entire length of connected robot arm. The whole length is motor to end portion of n^{th} arm of robot. The twisting in robotic elements is flexibility because of connection made between the actuating device and robot arms. This outcome is always rotation of element in general. This effect was experimentally proved when connected part movements is very fast [2]. Using linear spring the joint flexibility model was created (Spong, 1987, Yuan & Lin, 1990). Joint flexibility in robotic arm is inevitable for (a) dynamic part (b) control part.

The joint flexibility is come out from the system actuating devices such as drives, thin shafts, flexible belts, gears for transferring power from one part to other in a practical robotic application. But this flexibility is tough task to control in robots and also challenging (Spong,1987; Tomei,1991) with respect to heavy solid robotic arms. If flexibility in joint is ignored, the control is unsuccessful and transverse vibration affect the position and instability will spoil the system while in free motion, when interacting with an activity environment (Spong, 1989). Therefore, the joint flexibility is included in design of control of robotic flexible arm for real time applications. In a horizontal plane, the structural lightweight polymer composite flexible robotic arm with weight of payload at the end is rotating [3]. The practical experiment is conducted and observed with different joint stiffness co-efficient. The joint stiffness co-efficient is categorized into three cases, such as Case-1: stiffness coefficient $k_c = 0$ (rigid), Case-2: stiffness coefficient $k_c = 1$(flexible), Case-3: stiffness coefficient $k_c = 5$(high flexible). The amplitude of vibration and apparent deflection are observed.

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II. EXPERIMENTAL METHODOLOGY

The terminology adopted to this experimental setup is given in the Table -I. The actuator shaft is attached to the hub. The hub is attached to the composite single link flexible manipulator as shown in Fig.4.

The actuator shaft and gear arrangement are enclosed in a casing. This setup is acting as a flexible joint model. Flexibility in joint is energy storing device, which help the system for low energy utilization. This mathematical modelling is provided to formulate a dynamic equation of motion [4].

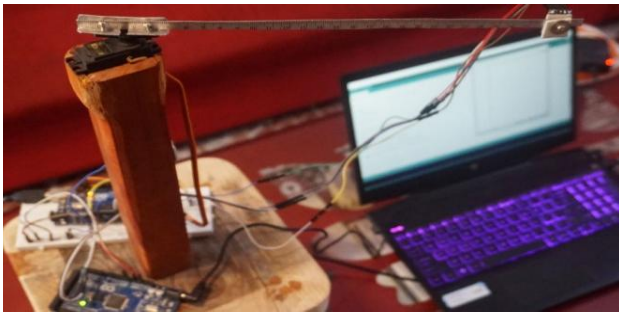

Fig. 1 Experimental Setup

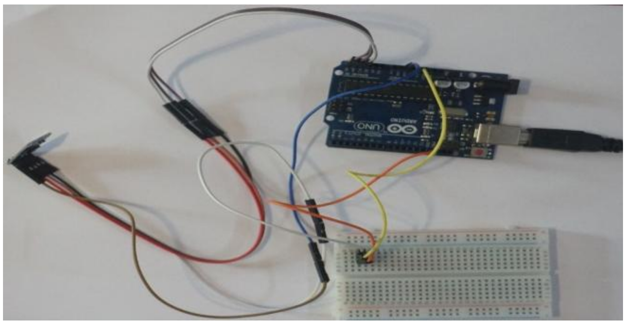

Fig.2 Accelerometer arrangement

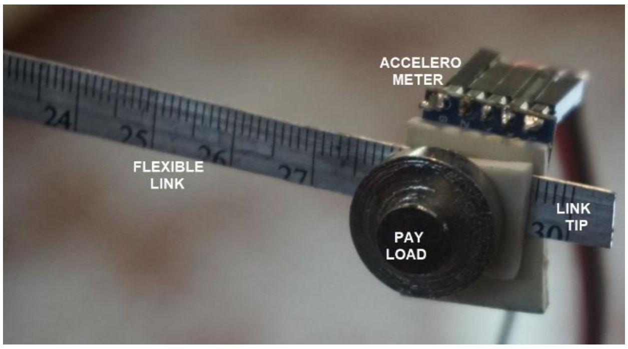

Fig. 3 Load attached at Tip

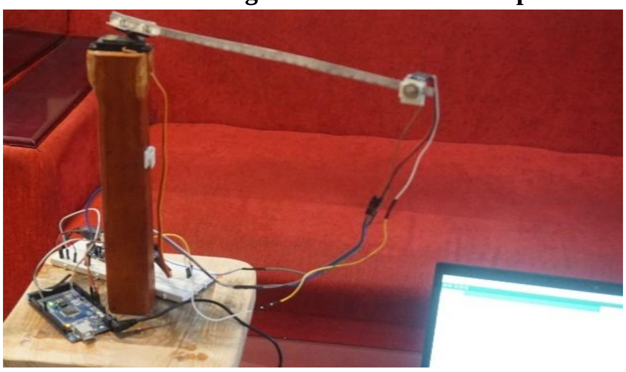

Fig. 4 Accelerometer at Tip

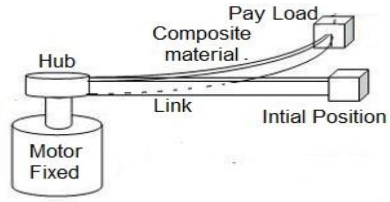

Fig. 5 Link rotational position

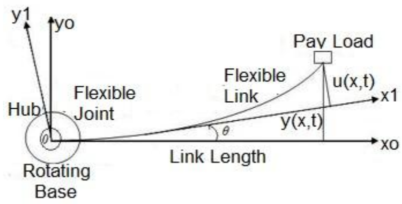

Fig. 6 Lightweight link terminology

Let the flexible link parameters are, length of link '*L'* in meter and mass density 'ρ' in length per metre (*kg/m)*. The modulus '*E'* (*N/m*^{2}) and '*I'* represents second moment of inertia (m^4) of link respectively as shown in Fig.5. The *X-0-Y* is the inertial co-ordinate frame and X_1 *-0-*Y_1 is attached to the rigid link in Fig.6. The angular deformed position of a rigid body is 'θ' and outward flexible deflection of the link is *u* (*x*, *t*). The 'M_p' denotes a payload attached at the end with payload inertia is 'I_p'. The base fixed actuator is attached to the joint. The hub inertia is 'I_h' and 'K_s' stiffness of a spring. The 'τ (*t*)' input rotating force in *Nm* is supplied to the motor. In a x-y plane the motor is revolving [5]. The motion equation is obtained by both Lagrange-Assumed mode approach [6].

A. State space Representation

Therefore, the reduced model could be used for the system control. For only considering first two modes of interest, the equation for state space model is stated as [7] - [8],

$$X^{\bullet} = AX + Bu \quad (1)$$

In the flexible link manipulator three sensors are attached. The first is facilitated at the end point acceleration, second for hub angle and the final one is for measure of hub angle velocity. The absolute deflection y (x, t) relates to state space as follows,

$$y\,(x, t) = [C]\,[X] \quad (2)$$

B. Experimental Apparatus

The apparatus listed below and PCBs are connected as per the experimental schematic illustration in Fig.7 and experiment is conducted with laboratory room ambient condition as shown in Fig.8 and observed the readings.

The required devices are (1) Motor servo MG 995 (360^o Rotation), (2) Arduino Mega 2560,
(3) ADXL 345 Accelerometer Digital, (4) Bread Board GL 12, (5) Printed kit Board L 298D, (6) Jumper cable 40 core M to F, and M to M, (7) PCB 101,
(8) Converter DC to DC 4051, (9) Printer cable USB 1.5M, (10) Con. PVC 10K, (11) Ad.12V 1Am RGP.

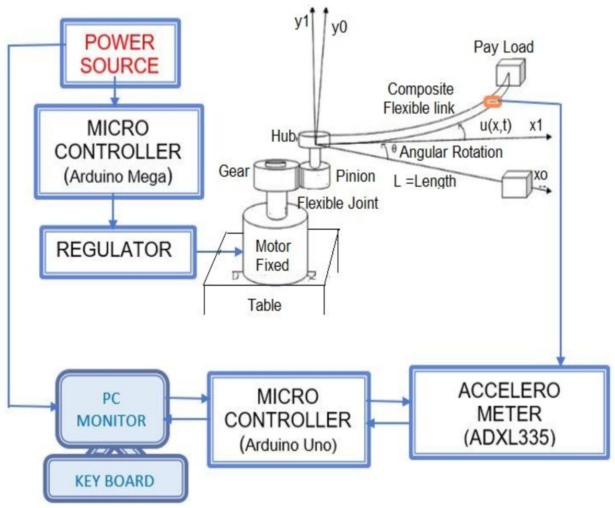

Fig. 7 Schematic of Experimental Diagram

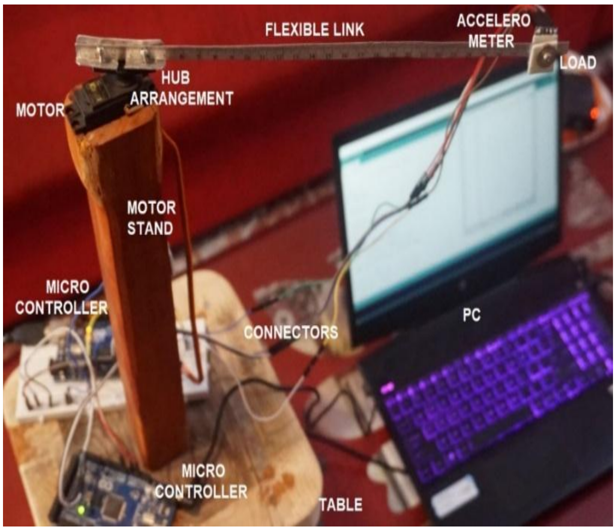

Fig. 8 Experimental Circuit and Setup

III. FLEXIBLE LINK MATERIAL

For the experimental validation and numerical confirmation, composite material is selected. By adding two or more fibres in a single matrix which yields new type material is known as hybrid composites. This type of new material has lightweight and good metal properties. The different fibre materials which are integrate into hybrid composite new type material. The new type material parameters of composite are given in the Table. The physical quantities of the composite material single link flexible manipulator are listed in the Table-I. The composite material robotic link tracking control is very challenges and PID, State feedback and Linear quadratic controllers are used to reduce the elastic vibration of the flexible arms [9].

Table- I: Composite flexible robotic arm manipulator and numerical values for simulation [10]

Parameter of Hybrid Composite	Symbol	Unit	Value of Systems
Hybrid composite length	(L)	m	1
Link Cross sectional area	(A)	m^2	1e-4
Hybrid composite flexible link mass	(m)	Kg/m	4.65e-4
Damping coefficient	(ζ)	m	0.015
Young's modulus	(E)	N/m^2	4645.15e-6
Moment of inertia (MOI) of a link	(I_a)	$Kg.m^2$	9.6e-6
Eqt. (MOI) at load	(I_e)	$Kg.m^2$	0.06751
Frequency of link	(ω_c)	H_z	3.2
Link Stiffness	(k_s)	N/m	0.7883
Eqt. viscous damping	(B_e)	-	0.199
Motor Efficiency	(η_m)	-	0.69
Armature resistance	(R_m)	Ω	2.6
E.m.f. torque constant	(K_m)	-	7.67e-3
System Gear Efficiency	(η_g)	-	0.9
Rotating Gear Ratio	(K_g)	-	70
Motor torque constant	(K_t)	-	7.67e-3

IV. DYNAMIC MODEL VALIDATION

The dynamic movement equation of a robotic arm with flexibility is derived as given below,

$$\begin{bmatrix} M_{rr} & M_{rf} \\ M_{fr} & M_{ff} \end{bmatrix}\begin{bmatrix} \ddot{q}_r \\ \ddot{q}_f \end{bmatrix} + \begin{bmatrix} C_{rr} & C_{rf} \\ C_{fr} & C_{ff} \end{bmatrix}\begin{bmatrix} \dot{q}_r \\ \dot{q}_f \end{bmatrix} + \begin{bmatrix} D_{rr} & 0 \\ 0 & D_{ff} \end{bmatrix}\begin{bmatrix} \dot{q}_r \\ \dot{q}_f \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K_{ff} \end{bmatrix}\begin{bmatrix} q_r \\ q_f \end{bmatrix} = \begin{bmatrix} B_r \\ B_f \end{bmatrix}\tau \quad (3)$$

The 'q_r' indicates rigid manipulator coordinate and 'q_f' flexible or elastic coordinate. By mathematical manipulation of an above equation, the feedforward compensator for the system is determined as given below,

$$\tau = M_{rr}\ddot{q}_r + M_{rf}\ddot{q}_f + C_{rr}\dot{q}_r + C_{rf}\dot{q}_f + D_{rr}\dot{q}_r \quad (4)$$

By refering the given path q_r, $\dot{q}_r$, and $\ddot{q}_r$, the input torque is supplied to arm joint is calculated by the torque force expression as already been given in the equation (3). The values of q_f, $\dot{q}_f$ and $\ddot{q}_f$ are unknown and treated as null and out results are plotted.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A. PID Control

The transfer function is operated with PID control. The block diagram of PID as shown in Fig.9. The MATLAB tool is used to control the system parameters. In the control system, using step input is applied to the actuator and their response characteristics are noticed. Fig.10 and Fig.11 gives the PID controller output response of a composite single-link manipulator. It is observed that the amplitude of vibration is reduced to 0.00459m. But the steady state time is found to be 45sec. This could be verified using PID controller by experimental method.

$$Y(s)/U(s) = G(s)*[K_p + K_d s + (K_i / s)] \quad (5)$$

Fig. 9 PID controller

Fig.10 gives the experimental values of PID controller output response of a composite single-link manipulator. It is observed that the amplitude of vibration is reduced to 0.00358m. But the steady state time is found to be 6.5sec. This is noticed from graphs, using PID controller by experimental method. But the system condition is critical as shown output response.

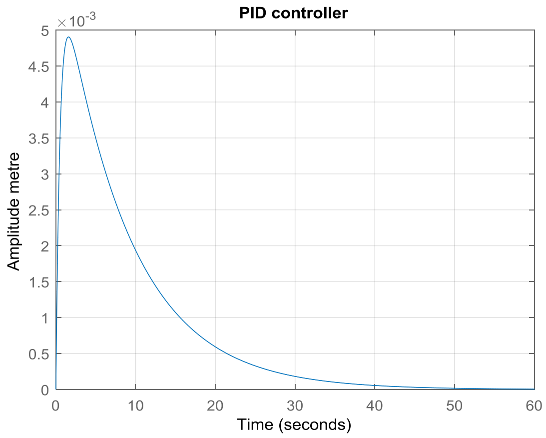

Fig. 10 PID controller simulation output

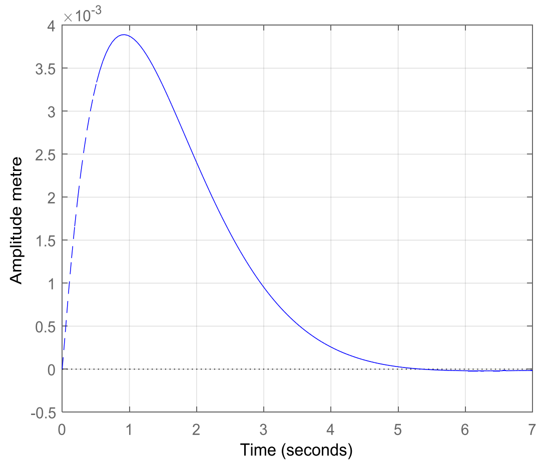

Fig.11 PID controller Experimental output

Table II- PID Simulation and Experimental Results

Flexible Link Material	Simulation		Experimental	
	amplitude in y-axis (m)	settling time in x-axis (sec.)	amplitude in y-axis (m)	settling time in x-axis (sec.)
Polymer Composite	0.00459	45	0.00358	6.5

B. State Feedback Control

The design of control system, the desired closed loop poles using pole placement approach with different set values are identified. The output responses are noticed and best suited pole is selected for control the system. The feedback control block diagram is given Fig.12.

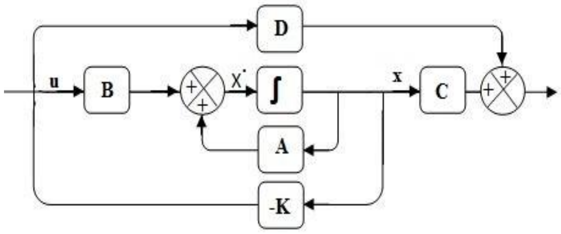

Fig.12 Feedback control block diagram

The Fig.13 shows the result of simulation and output of experimental values of state feedback controller of a composite link manipulator. It is observed that the amplitude of vibration is 1.1m at the time t is 1.25sec. The transient period is up to 2.5sec. But the steady state time is starts from 2.5sec. The amplitude of vibration and steady state period could be minimized further. The time in x-axis and output value of an amplitude of vibration in y-axis.

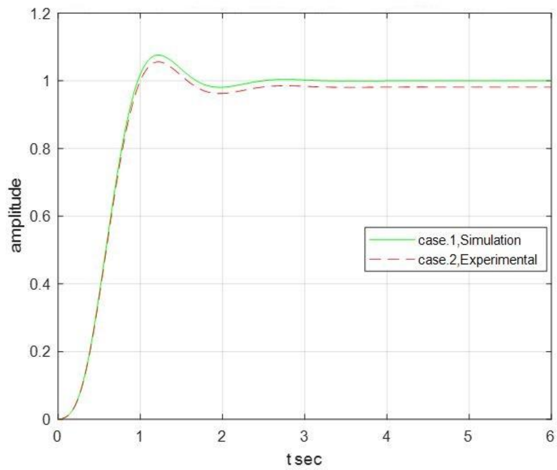

Fig. 13 Experimental result of state feedback

In Fig.13, the dotted line is experimental output response of state feedback controller of a composite link manipulator. It is observed that the amplitude of vibration is 1.01m at the time (t) is 1.25sec. The transient period is up to 2.9sec. But the steady state time is starts from 3sec. The amplitude of vibration and steady state period could be minimized further for precision and accuracy, but the system is under critical condition. The time taken in x-axis and amplitude in y-axis.

Table III- State Feedback Experimental Results

Flexible Link Material	Simulation Results		Experimental Results	
	Amplitude in y-axis (m)	settling time in x-axis (sec.)	amplitude in y-axis (m)	settling time in x-axis (sec.)
Polymer Composite	0.10	0.80	0.05	0.70

C. Linear Quadratic Optimal Regulator control

It is observed that using the LQR controller the system tracking and approaches to steady state within 0.1 sec. The amplitude of 0.15m.

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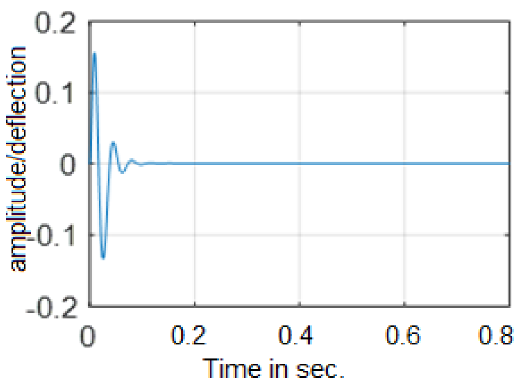

Fig. 14 Optimal LQR step response

The LQR is used to control the system and attained a steady period of 0.1 sec, the output response as shown in Fig.14. The amplitude of vibration of aluminium flexible link is 0.35m and hybrid composite link is 0. 13m.This is taken in the time domain of 0.6sec.

Table- IV Response of controller in Time Domain of 0.6sec.

without controller		
Materials	Amplitude (m)	Time (sec.)
Aluminium	0.350	0.6
Composite	0.130	0.6

Table -V Response of controllers

	Using Controller					
Composite material	PID		State Feedback		LQR	
	Amplitude (m)	Settling time (sec)	Amplitude (m)	Settling time (sec)	Amplitude (m)	Settling time (sec)
	0.00449	50	1.08	2.5	0.11	0.1

The effect of PID, state feedback and linear optimal quadratic regulator (LQR) controls are plotted for the same time domain 0.6sec. The vibration amplitudes are listed in the Table -V.

15% reduction in the amplitude of vibration is obtained by the linear quadratic optimal control system in dynamic analysis of one link flexible system and steady state is achieved as fast 0. 1sec.This will lead to the precision and accuracy of flexible robotic link manipulator with lightweight characteristics.

D. Hub angle and Link velocity

Using, linear quadratic regulator control, a unit step response to one arm flexible robotic manipulator. This illustration in the Fig.15. From the plot the following results are observed. In x-axis is time in sec. up to 8 sec. and y-axis is hub angle, link deflection/amplitude, velocity and acceleration. Substitute *K* value optimal matrix. The step output behaviors LQR is shown in Fig.15. Observed that the angle is steady with quick time.

From plot it is observed that the system without oscillation or without overshoot hub rotation angle is stable to the desired position quickly. The arm deflection of the system is settled smoothly as in Fig.16.

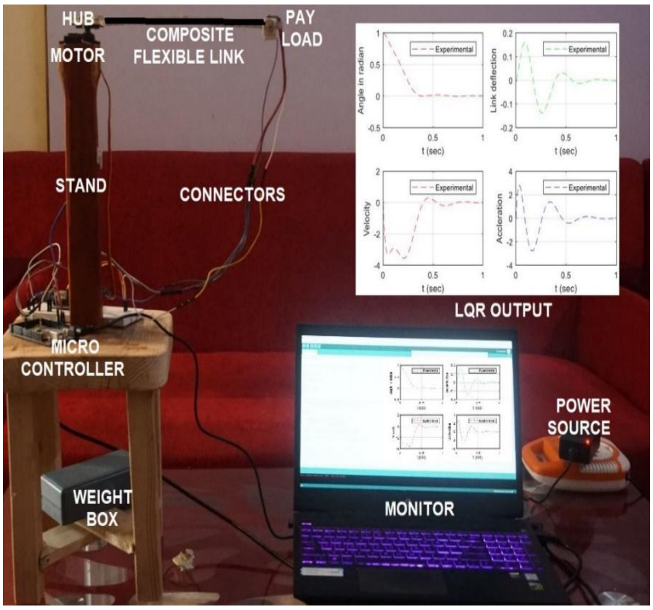

Fig.15. LQR Experimental output

The velocity of the hub rotation and velocity of the deflected arm almost same i.e. 1.2sec.

The real value of

$x_1 = \theta_1$,

$x_2 = \theta_2$,

$x_3 = \dot{\theta}_1$ and

$x_4 = \dot{\theta}_2$ indicates gear or hub angle, and apparent deflection, angular velocity and velocity of link. These values are noted from the plots and tabulated in Table -VI and Table -VII.

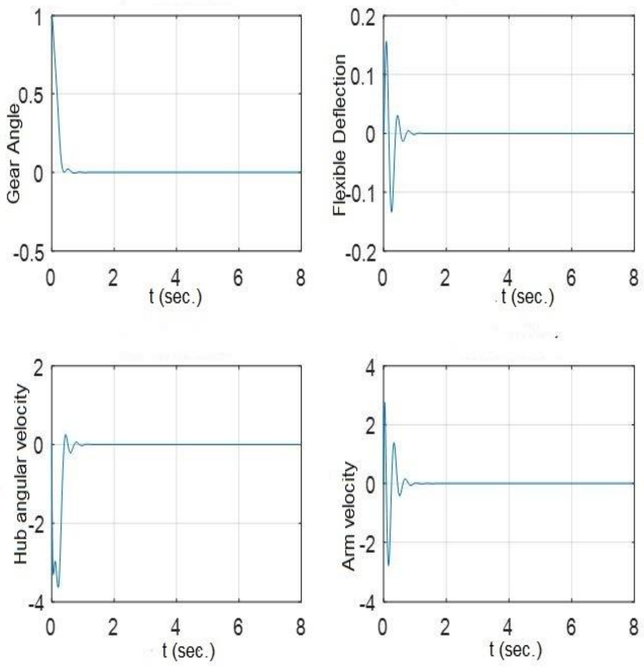

Fig. 16 LQR Simulation Output.

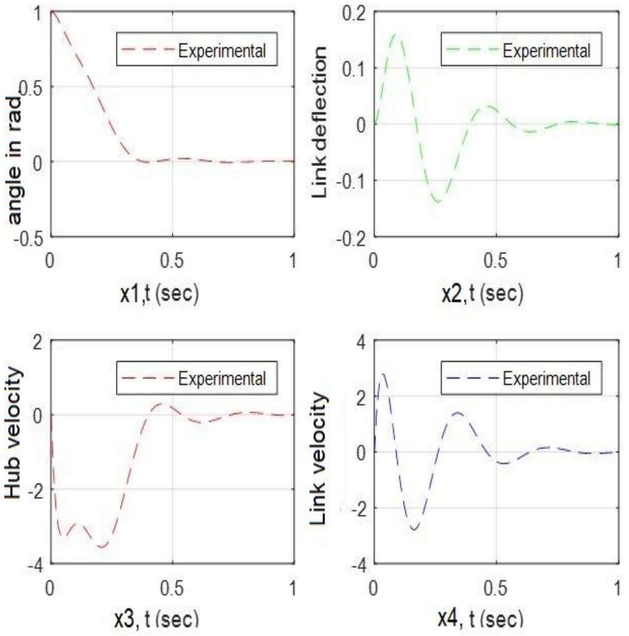

Fig. 17 LQR Experimental Output

Table VI- Experimental Results for Hub angle and Tip Deflection

System parameters	Simulation		Experimental	
	(y) axis	(x) axis	(y) axis	(x) axis
	Output in rad.	Time in sec.	Output in rad.	Time in sec.
Hub/Gear angle(rad)	0.10	0.80	0.05	0.70
Link deflection(m)	0.17m	0.90	0.17m	0.75

Table- VII Experimental Results for Velocity

System parameters	Simulation		Experimental	
	(y) axis	(x) axis	(y) axis	(x) axis
	Output in m/s	Time in sec	Output in m/s	Time in sec.
Angular velocity(m/s)	0.20	0.80	0.40	0.79
Link velocity(m/s)	3.00	1.00	2.90	0.90

VI. CONCLUSION

The experimental method is conducted to validate the hybrid material of composite arm behavior for robotic link application. The control methods are implemented and output responses are obtained.

For controller part, a general MATLAB code has been created and numerical simulation programme is carried for vibration of amplitude reduction. The amplitude of vibration from simulation result as well as experimental output were compared. The experimental values very close to the calculated values. The MATLAB helps to reduce the steps of programme coding to describe flexible arm dynamics which controls the design calculation cost.

The joint flexibility stiffness coefficient such as rigid joint (kc =0), joint is flexible (kc =1), more flexible joint (kc =5) are employed for simulation. The output values are shown.

The flexibility in joint of robotic arm adding with structural flexibility both involve a major role to varying the motion of an end portion of flexible arm while doing activity in an environment place.

For control of composite link, a model-based three categorized controllers were implemented to control the end point of a flexible arm robotic manipulator (i) progressive -integral-derivate (P-I-D) Control (ii) Stable feedback (SF) Control (iii) Optimal Linear Quadratic Control (LQR).

The SF and PID model controllers were yield good results in end point path tracking of flexible robotic composite material arm. But arm end point vibration was abnormal noticed.

It is observed from the experiment output that the LQR model control follows an improved path chasing and clampdown of robotic arm tip shaking when compared to other controllers drastically.

These vibration models were subjected to stability check and control using (PID) control system and modern controls namely SF controller and optimal LQR. The system subjected to time and frequency domain analysis for stability check, the plant was observed to be unsteadiness. To control the end point elastic deformation of a robotic arm, model based three categorized controllers were designed. Compared to all the various control design, the quadratic optimal regulator yields good result for flexible one-link composite material robotic link end effectors.

Reduction of 15% amplitude of vibration is obtained from the linear quadratic optimal controller system for motion investigation of flexible arm manipulator plant and the steady state is achieved as fast as 0. 1sec.This will lead to the precision and accuracy in the design of flexible robotic link manipulator with lightweight characteristics.

Composite Parameter in meter	Calculation without controller	Simulation response	Experiment response
amplitude	0.13	0.11	0.16

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