"Development and Analysis of Two Degree of Freedom Robot Arm Made By Composite Material"

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ABSTRACT

In this paper static and dynamic analysis of a flexible two degree of freedom revolute-prismatic joint robot arm is investigated. Here, 2D robot arm is modelled considering the properties of aluminium and graphite/epoxy composite material. The flexible arm is assumed to carry out a time varying end mass. The dynamic equation of motion of flexible robot arm is obtained by Euler-Lagrange equation of motion. Effect of rotary inertia, gravitational has been considered in developing the dynamic model .Equation of motion solved by finite element formulation. A computer program using MATLAB is developed for numerical simulation. Static and dynamic analysis results of robot arm obtained in ANSYS are presented in graphical form. The results obtained indicates graphite/epoxy robot arm bears high stiffness and minimal deflection while achieving a significant weight reduction when compared to aluminium robot arm of the same size and capability

KEYWORDS: ANSYS, MATLAB, Degree of freedom, Dynamic analysis, Numerical analysis

1. Introduction

Metallic robotic arms or manipulators, currently dominate automated industrial operations, but due to their intrinsic weight, have limited usefulness for large-scale applications in terms of precision, speed, and repeatability.

Many researchers have explored the application of lightweight composite materials to the design of robotic arms. Lee et al. [1] had designed and built a SCARA-type direct drive robot using graphite/epoxy. They have shown that, in addition to weight savings, the static deflection, natural frequency of vibration and damping ratio were superior in the composite arm compared to its aluminium predecessor. Gordaninejad et al. [2] have addressed this issue using Hamilton's Principle and Timoshenko beam theory to derive equations of motion of a laminate composite flexible robotic arm that take into account the effects of geometric nonlinearity, rotary inertia and shear deformation.

K.Krishnamurthy et al. [3] studied the simulation of single link robot fabricated from orthotropic composite materials and concluded, the torque required for manoeuvre was substantially less for composite materials and the motion induced displacement of composite arm was substantially less than steel, aluminium. Ghazavi et al. [4] studied on the enhancement of end effectors positional accuracy of high speed light weight flexible three dimensional robot manipulator. It is observed that the construction of flexible link from advance composite material has significantly reduced residual vibration in the end effector. Jasjit Kaur et al. [5] presented optimization of robot arm movement by Genetic Algorithm for reducing energy consumption criteria. He did simulation study on the three link manipulator for easy movement of manipulator between different coordinates and to control the accuracy of end effector.

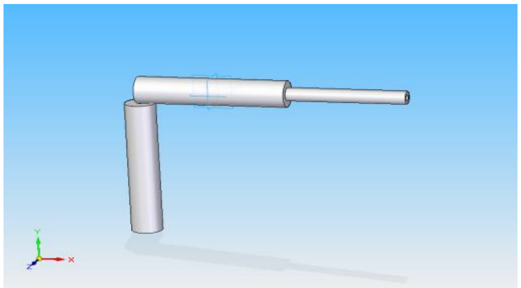
Elenor et al. [6] did numerical simulation of two and three link planar robot arm for both open and closed chain mechanism. He revealed that, at low speeds slider inertia effects negligibly and significantly at high speeds. Wen Chen et al. [7] have done verification study on magnitude and torque of flexible robot manipulator and how these parameters effect the displacement of the links. N G Chalhoub et al. [8] performed examination study of the combined effects of rotary inertia and shear deformation of revolute flexible robot arm made from laminated composite material. Samolinos et al. [9] did experimental validation on three degrees of freedom flexible robot arm having dynamical and kinematical features similar to the PUMA560 industrial robot. In the dynamic analysis on flexible two link robot deformation occurs at the end point of each link and deflection as well as torque both got effected by boundary conditions [10].

S.Vaidyaraman et al [11] did experiment on three degrees of freedom revolute robot manipulator. Considered the third link only flexible and made up of orthotropic composite material and system dimensions as $g=9.81m/s^2, m=0,0.3kg, m_2=1kg, Q_y=0,2,10N, I_{1xx}=0.1234m^4, I_{2yy}=0.0131m^4, I_{2xx}=0.0004m^4$ $l_2= 0.207m$, $l_3=0.8m$, h=0.01m, b=0.01m. By the analysis study he came to know that damping of Graphite/Epoxy arm has a significant effect on the vibration of the tip of robot manipulator. He showed that bending stress and displacements are highly dependent on the angle of fiber orientation and material properties. Xuping Zhang et al. [12] presented strategic study report on motion planning of flexible manipulator. He proposed the concept of redundant configuration. By comparing the numerical simulation results of initial configuration method and self motion planning, he showed that strategy of redundant configuration is best in controlling the motion error of flexible manipulators. E Abedi et al. [13] presented dynamic simulation study on rigid and flexible robot manipulator and shown dynamic behaviour of flexible manipulator and deformation and displacements of flexible link are very good by the rigid link. R Ghayour et al. [14] performed numerical analysis on tapered rotating multilayered composite beam. Through numerical studies he investigated dimensionless parameters from the equation of motion and their combined effect on modal characteristics of the rotating composite beams. Compared the results and got conclusion that more accuracy can be achieved by the hierarchical FEM with smaller number of elements than conventional FEM.

This paper focuses on exploring the feasibility of using graphite/epoxy composite material for the construction of robotic arm. The cross-sectional geometry of the links of the arms is analyzed for optimal stiffness and strength-to-weight ratios that are capable of preserving high precision and repeatability under time-dependent external excitations. The dynamic response of joint velocities and end effector deflection of a two degree-of-freedom graphite/epoxy composite material robot arm is presented. Finite element analysis (FEA) is performed on a 2D robot arm and compared the results of analysis for aluminium and graphite/ epoxy composite material.

2. Description of Dynamic Model Developed

For static and dynamic analysis purpose 2 DOF robot arm model created in ANSYS12.1. The model consists of base, link1 and link2. Link1 is rotating and link2 is sliding in link1. The 3D model and ANSYS models are shown in figure 2.1 and 2.2.



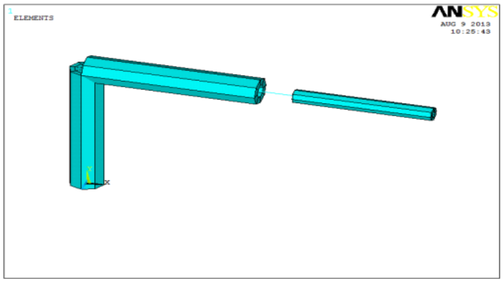


Fig. 2.1 3D model of robot arm

Fig.2.2 Ansys model of robot arm

2.1 Dynamic Equation

The material properties and geometric dimensions of the system are given in table. 2.1 The purpose of simulation studies is to examine the effect of the elastic deformation, end effector deflection when arms are manufactured with light structure links of hollow cross section made up of graphite/epoxy composite and to demonstrate the advantages of incorporating composites in the structural design of robotic manipulators.

Table 2.1: Material properties and Geometric properties of links of robot arm [8]

Geometric Properties	**Unit in 'm'**	**Material Properties**	**Value**
Outer diameter of link1	0.1	Mass density of Aluminium	2.643×10^3 kg/ m^3
Inner diameter of link1	0.05	E of Aluminium	0.7×10^{11} N/m²
Length of rotating link1	0.5	G of Aluminium	0.26×10^{11} N/m²
Outer diameter of link2	0.05	Mass density of Graphite/Epoxy	1.3×10^3 kg/m³
Inner diameter of link2	0.025	E of Graphite /Epoxy	1.727×10^{11} N/m²
Length of sliding link2	0.4	G of Graphite/Epoxy	0.037610^{11} N/m²

2.2 Finite Element Formulation

The two links are divided into 'j' number [10] of element with the idealization of beam elements. The number of nodes made is 'k'.

Then the finite element equation is given by Eq.1.

$M_a + K_a = F(t)$ .... Eq. (1)

The solution of finite element equation can be sought with Eq.2.

$a = A \sin wt$ .... Eq. (2)

Where A is nodal displacements vector which is given by Eq.3.

$$A = \begin{bmatrix} a_1 \\ a_2 \\ . \\ a_k \end{bmatrix} \quad \text{.......... Eq. (3)}$$

Where, **M** is Global mass matrix; **K** is Global stiffness matrix and **F** Global load vector.

The each element Mass Matrix 'M' is given by Eq.4.

$$M^{j} = \begin{pmatrix} \frac{\rho A l}{3} & 0 & 0 & \frac{\rho A l}{6} & 0 & 0 \\ & \frac{13\rho A l}{35} & \frac{11\rho A l^2}{210} & 0 & \frac{9\rho A l}{70} & \frac{-13\rho A l^2}{420} \\ & & \frac{\rho A l^3}{105} & 0 & \frac{13\rho A l^2}{420} & \frac{\rho A l^3}{140} \\ & \text{Symmetry} & & \frac{\rho A l}{3} & 0 & 0 \\ & & & & \frac{13\rho A l}{25} & \frac{-\rho A l^2}{210} \\ & & & & & \frac{\rho A l^3}{105} \end{pmatrix} \quad \text{... Eq. (4)}$$

Each Element Stiffness Matrix 'K' is given by Eq.5.

$$K^{j} = \begin{pmatrix} \frac{EA}{l} & 0 & 0 & \frac{EA}{l} & 0 & 0 \\ & \frac{12EI}{l^3} & \frac{6EI}{l^2} & 0 & \frac{-12EI}{l^3} & \frac{6EI}{l^2} \\ & & & 0 & \frac{-6EI}{l^2} & \frac{-2EA}{l} \\ & \text{Symmetry} & & & \frac{12EA}{l^3} & \frac{-6EI}{l^2} \\ & & & & & \frac{4EI}{l} \end{pmatrix} \quad \text{... Eq. (5)}$$

The natural frequencies ωi of overall manipulator can be [8] obtained with the following equation Eq.6.

$[K - \omega_i^2 M] = 0$, i = 1 to k .... Eq. (6)

The amplitude equation for each natural frequencies 'ωi' is given by Eq.7.

$$[K - \omega_i^2 M][A^i] = 0$$ .... Eq. (7)

From the amplitude equation, the Amplitude vectors are for each frequency obtained as 'Ai'.
The Amplitude vectors are normalized with following relations as given below

$$A_N^i = \frac{A^i}{\sqrt{S_i}}$$ Where

$$S_i = [A^i]^T [M] A^i$$

Then the normalized vector of all amplitude can be written as shown in Eq.8.

$$A_N = [A_N^1 \quad A_N^2 \quad . \quad . \quad A_N^k]$$ .... Eq. (8)

The global load vector 'F' is written as shown in Eq .9.

$$F = \begin{pmatrix} F_{1x} \\ F_{1y} \\ 0 \\ F_{2x} \\ F_{2y} \\ 0 \\ . \\ . \\ F_{kx} \end{pmatrix}$$ .... Eq. (9)

Note that each term of Force vector is to be expressed as shown in Eq.10.

$F = F_0 \text{ Sin } \omega t$ .... Eq. (10)

The inertia forces at nodes corresponding to COG are obtained with accelerations which are found from dynamic equation and are given by Eq.11.

$$F_x(t) = \begin{bmatrix} m_1 & X_{1g} \\ m_2 & X_{2g} \end{bmatrix}$$

$$F_y(t) = \begin{bmatrix} m_1 & Y_{1g} \\ m_2 & Y_{2g} \end{bmatrix}$$ .... Eq. (11)

Some F the nodal forces may be taken as Zero based on the nodal boundary conditions.

The normalized Force vector '**f**' is obtained by Eq.12.

$f = A_N F$ .... Eq. (12)

The generalized matrix 'P' is obtained by Eq.13.

$$P = \frac{f\,(m,1)}{(\omega_m^2 - \omega^2)}\ ,\ m = 1 \text{ to } k \qquad \text{.......... Eq. (13)}$$

The final solution, i.e. nodal amplitude vector is calculated by Eq.14.

$$A = A_N\, P \qquad \text{………. Eq. (14)}$$

3. Result and Discussions

3.1 Numerical results of 2D robot arm

In the following, numerical results are presented for a two DOF revolute-prismatic, flexible robot arm. Two models have been considered with the manipulator made up of two materials. Hollow circular beam elements made up of aluminium is termed as model-l and manipulator made up graphite/epoxy is termed as model-2. The effect of the flexibility of the links of both aluminium and graphite/epoxy robot arm behaviour is illustrated by comparing the joint velocities and end effector deflections obtained from these two different models of the robot manipulator. The force and torque, is applied at the joints of the manipulator in all cases.

The torque versus time for rotary joint 1 and force versus time for sliding joint 2 is presented in figure 3.1a & b. The variation of applied input values of torque and force indicate that input at joints is gradually increases and then suddenly brought to zero this is due to reaching of arm to the said in[3][4].

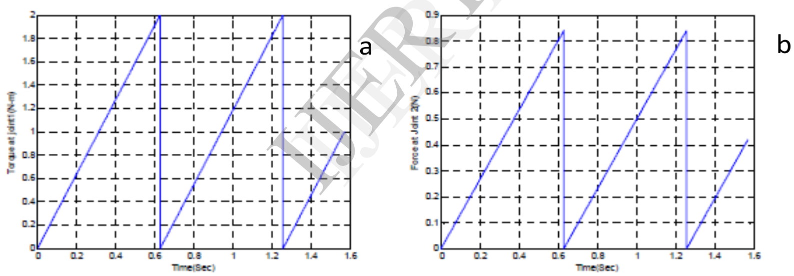


Fig 3.1: Applied Joints inputs torque/force.

The results MATLAB of the two models which includes the flexibility of both links . A comparison of the simulation results shows that the effect of the flexibility in links causing vibratory motion. Comparisons among figure 3.2 a & b shows that the torque required to move the arm of the manipulator constructed from graphite/epoxy is less that torque needed to move the manipulator with an aluminium arm. This is because of reduction in the torque is mainly due to the lighter weight of the graphite/epoxy compared to aluminium.

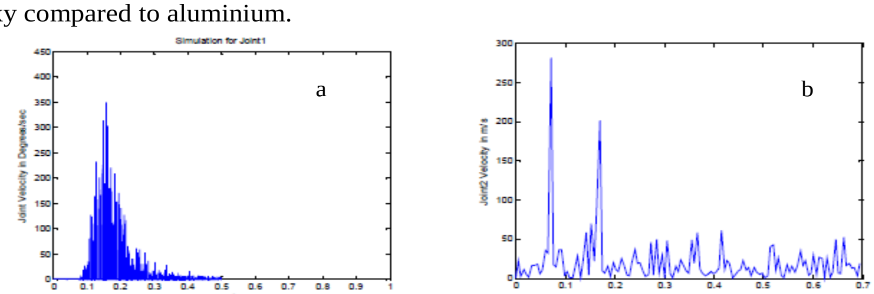


Fig 3.2: Joint velocities of a) aluminium and b) graphite/epoxy robot arm.

The accuracy of the end effector deflections predicted by models is also assessed. This is performed by comparing the results obtained from the aluminium and the graphite/epoxy models of the robot arm when subjected to the applied torque and force. The results are illustrated in figure 3.3 a & b. The graphite/epoxy model exhibits higher frequency and higher amplitude than the aluminium model at steady state. However the deflection variation continued in aluminium model. This indicates that the faster and less oscillatory response is obtained by the graphite/epoxy robot arm and energy stored in it would be dissipated quickly.

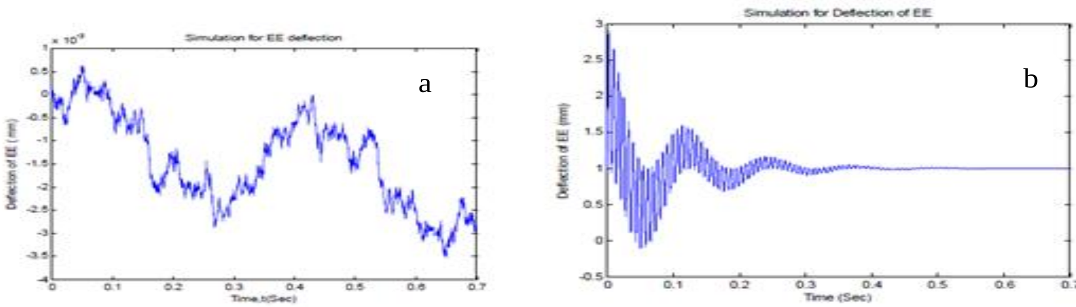


Fig 3.3: Deflection of end effectors aluminium (a) and graphite/epoxy (b) robot arm.

The superiority of advanced graphite/epoxy over conventional metals is demonstrated by comparing the response of an aluminium arms to the response of a graphite/epoxy arms. A valid comparison between the performance of manipulators which are made of aluminium materials and graphite/epoxy materials is done by prescribing the deflections of end effector of the robotic arm shown in figure 4.3. This is because graphite/epoxy is lighter than aluminium and the application of a set of torque and force to the robot arm would generate higher speed, and consequently, higher inertial forces in the graphite/epoxy arm than in the aluminium one.

3.2 Comparison of FEA results

3.2.1 Displacement of 2D robot arm for link 2

The comparison results of displacement for 2D robot arm for both aluminium and graphite/epoxy composite is shown in figure 3.4. The results showed 10% reduction of time in case of graphite/epoxy robot arm compared to aluminium arm and aluminium robot arm link2 reaching 0.0412 m at 0.8 second of time interval, whereas, graphite/epoxy arm taking 0.70 second of time.

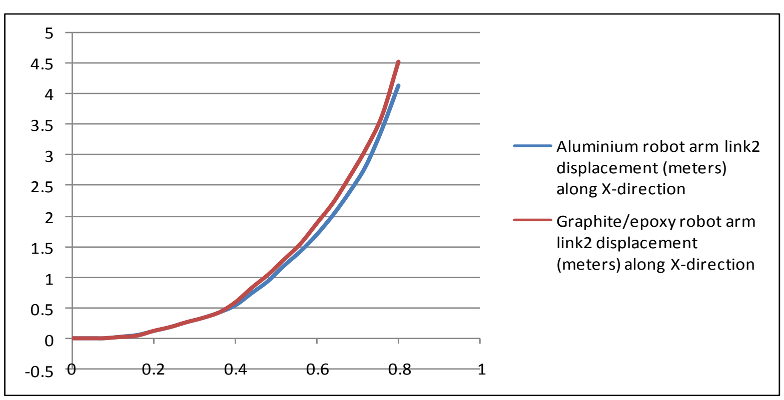


Fig 3.4: Displacement comparison of aluminium and graphite/epoxy/robot arm link2

3.2.2 Velocity of 2D robot arm for link 2

The comparison results of velocity for 2D robot arm for both aluminium and graphite/epoxy composite is shown in figure 3.5.The results showed 50% increment of velocity in case of graphite/epoxy than aluminium robot arm that is , aluminium robot arm link2 obtained 0.1624m/s velocity in 0.8 seconds of time and graphite/epoxy robot arm obtained 0.3462m/s.

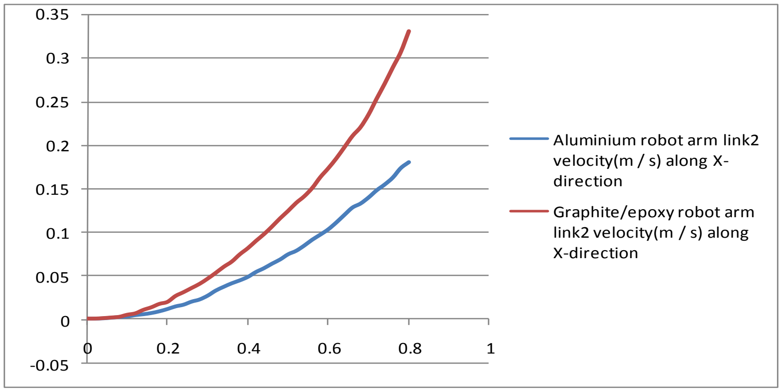


Fig 3.5: Velocity comparison of aluminium and graphite/epoxy robot arm link2

3.2.3 Acceleration of 2D robot arm for link 2

The comparison results of acceleration for 2D robot arm for both aluminium and graphite/epoxy composite is shown in figure 3.6. The results showed 10% acceleration increment in case graphite/epoxy robot arm than aluminium arm that is, aluminium robot arm link2 obtained acceleration of 0.3964m/s^2 in 0.8 second of time where as graphite/epoxy robot arm obtained 0.4238m/s^2.

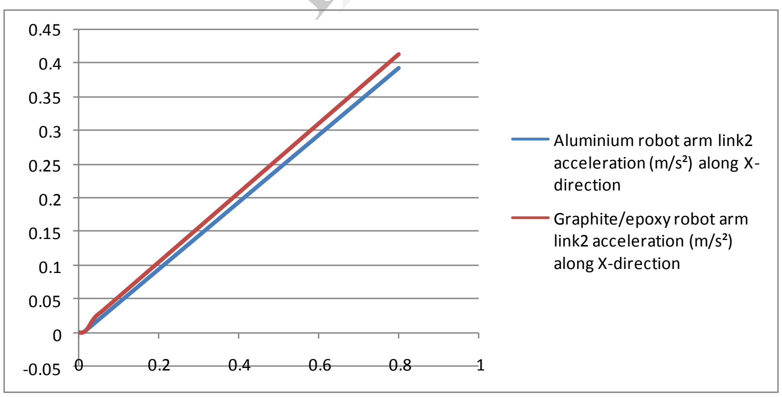


Fig 3.6: Acceleration comparison of aluminium and graphite/epoxy robot arm link2

3.2.4 Velocity of 2D robot arm for link 1

The comparison results of acceleration for 2D robot arm for both aluminium and graphite/epoxy composite is shown in figure 3.7.The results showed 80% velocity increment in case of graphite/epoxy than aluminium robot arm that is, aluminium robot arm velocity gradually increases obtaining the velocity of 1.612 m/s but in case of graphite/epoxy robot arm velocity suddenly increases reaching the value to 1.986 m/s and kept constant.

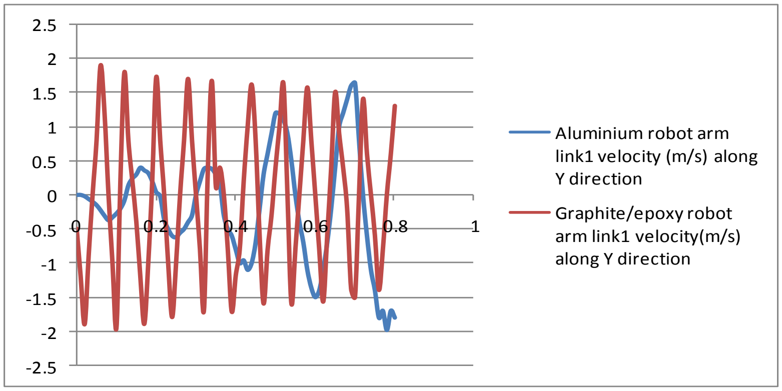


Fig 3.7: Velocity comparison of aluminium and graphite/epoxy robot arm link1

3.2.5 Acceleration of 2D robot arm for link 1

The comparison results of acceleration for 2D robot arm for both aluminium and graphite/epoxy composite is shown in figure 3.8. The results showed 60% acceleration increment in case of graphite/epoxy than aluminium robot arm i.e. aluminium robot arm link1 acceleration gradually increases reaches to value 0.962 m/s^2 but, in case of graphite/epoxy robot arm acceleration suddenly increases to a value of 1.6324m/s^2 and kept constant.

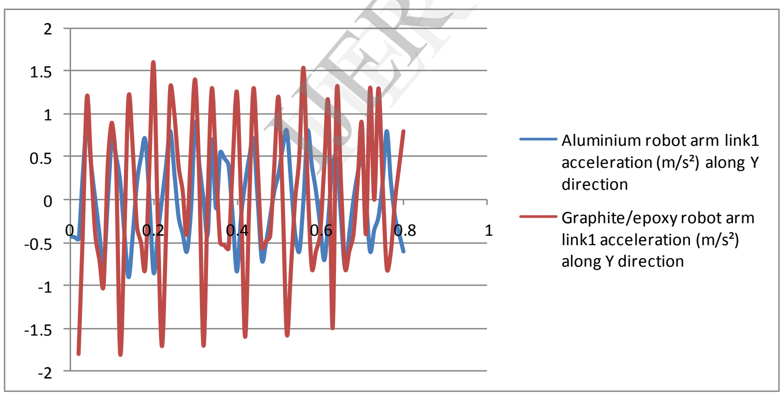


Fig 3.8: Acceleration comparison of aluminium and graphite/epoxy robot arm link1

4. Conclusion

This project outlines the design of a flexible 2-DOF robotic arm made of graphite / epoxy composite material. The static and dynamic analysis results shows that composite material robot arm is much more faster, lighter and has more accuracy and high bending stress than aluminium. Finally concluded graphite/epoxy is much better than traditional metals for constructing robots in all aspects. It was shown that static and dynamic deflections can significantly be reduced by constructing the robot arm from graphite/epoxy composite material. It was also demonstrated that the required torques and forces to move the manipulator to its desired position was greatly enhanced by constructing the robot arm from graphite/epoxy composite rather than aluminium. Based on the numerical and FEA results, following conclusions are made

1. The FE analysis showed that the rate of change of displacement, velocity, accelerations and bending stresses are within limiting values.
2. The effect of the flexibility of links on motion of the manipulator is significant and cannot be ignored in the context of accurate path track of end effector.
3. In addition, the inclusion of the flexibility in the links of the arm leads to an overestimated end effector deflections at steady state.
4. The use of advanced graphite/epoxy material in the fabrication of lightweight and high speed. Robotic manipulator leads to improved end effector positional accuracy and to lower torque/force requirements at the joints.
5. Graphite/epoxy material properties in the design of a robot arm play an important role in the reduction of the end effector deflections and in obtaining greater velocity and acceleration.

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