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Analysis of Lightweight Materials for Robot Manipulators

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ABSTRACT

The fabrication of lightweight robot arms and the ability of robotic devices to dissipate residual vibrations at the termination of a maneuver have both been highlighted as key research problems in recent reports. Computer aided engineering methods must be used effectively in the design and analysis process since the robot design has various parameters. The dynamic behavior of the mechanical elements used in Industrial Robots is extremely important for defining the overall performance. From this perspective, the material used for these elements is very important. This study shows the overall difference between using a composite material and the traditional aluminum for the design of the robot elements

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INTRODUCTION

Research on lightweight robot manipulators has increased dramatically in recent years, motivated In part by the expectation to achieve higher speed, less weight, which results in a lower energy Consumption, smaller actuators and higher payload to weight ratio. These issues are most relevant in the design of new-generation robot manipulators for manufacturing and spatial applications. In terms of materials being used for designing and manufacturing of industrial robots, aluminum is widely used, because of its good mechanical properties. For industrial robot design, a material with low density and high stiffness is always preferred. Aluminum meets these properties, in comparison with Steel or other metals. Composite materials, although harder to manufacture, can provide superior properties.

One of the basis study related to robot design is presented by Thomson (1984). In his study, he investigated the requirements of the designers and users of such equipment and attempted to evaluate current work in this field. Vukobratovic, Potkonjak, Inoue & Takano (2002) discussed kinds of robot driving systems and described CAD systems for industrial robots. They explained the principles of advanced robot design. Mir-Nasiri (2004) suggested a new design of a robotic arm with a parallel structure, but with a functional or geometry similar to the serial structure of a SCARA robot. Mrozek (2003) described two approaches towards designing interdisciplinary Mechatronic systems. Clark & Lin (2007) proposed a CAD-based integration method for analyzing and verifying the design of robotic mechanisms

Materials Used in Robot Manipulators:

In terms of materials being used for designing and manufacturing of industrial robots, aluminium is widely used, because of its good mechanical properties. For industrial robot design, a material with low density and high stiffness is always preferred (Ristea, 2010). Aluminium meets these properties, in comparison with Steel or other metals. Composite Materials, although harder to manufacture, can provide superior properties regarding stiffness and density. The table below shows a comparison between Aluminium and a Carbon Fiber Composite.

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Table 1: Material comparison

Material	Mechanical properties	
	Density (kg/m3)	*Elastic Modulus (GPa)*
Aluminum 6063 – T6	2700	70
Carbon Fiber (70%) Composite	1600	140

Structural Design and Characteristics:

The traditional heavy and rigid robots are designed with stiff links, so that the link's dynamics can be neglected, and therefore the tip position can be geometrically acquired from the joint's positions at any given moment in time. In flexible robotics the links are no longer assumed to be rigid and when it moves, unwanted vibrations appear due to elastic deformation. These vibrations can cause an error in positioning the tip of the robot. How to control the system to accurately position the end point has been a subject of much research in the past. In which materials used for it plays a vital role in increasing the efficiency of the robot.

Rigid robots are typically collocated systems, that is, the actuators and sensors are located at the same location (i.e., a joint). In the case of flexible robots this is not always the case. Most of the flexible robots are non-collocate (actuators and sensor are at different locations), being one of the first developed by the authors of the work in (Cannon and Schmitz, 1984).

Non-collocated systems exhibit Non-Minimum Phase (NMP) behavior which results in zeros in the right-half of the s-plane and as it is well known, unstable zero dynamics results in limitations on the achievable performance and stability (Cannon and Schmitz, 1984). Some researchers examined different techniques to change the system characteristics from NMP to Minimum Phase (MP).

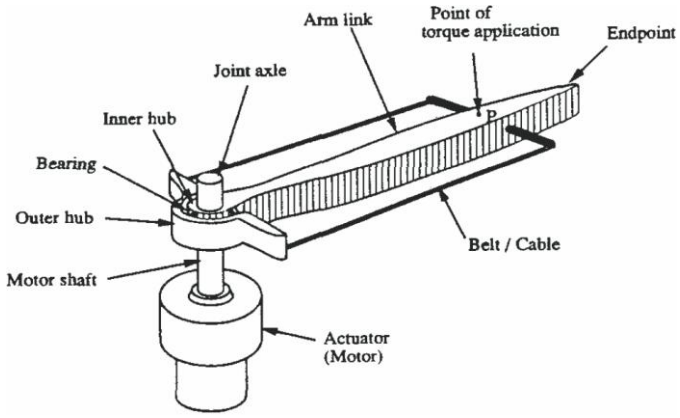


Fig. 1: Flexible link with torque transmission mechanism. From (Asada *et al.*, 1991).

Integrated Analysis of Design:
Three Axis Serial Manipulator (DEU-3X2-550):

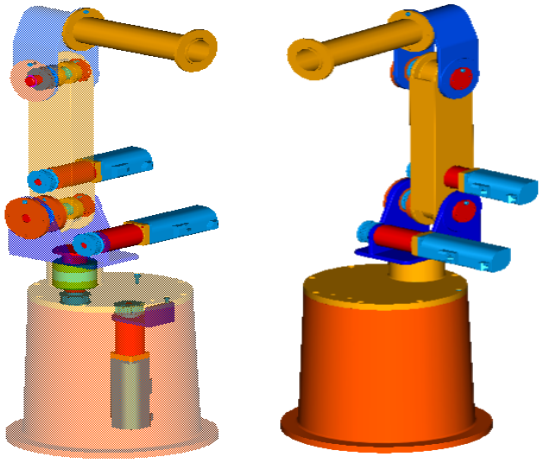


Fig. 2: Detailed design model of the robot.

Kinematic analyses of the robot manipulator are carried out by Cosmos Motion software. Axis angular velocities are calculated for desired maximum end point velocity. These are the necessary inputs for the selection of motors and gears. Desired end point velocity is chosen as 2000 mm/s for this robot. Kinematic analyses are performed for different trajectories. These trajectories pass through the maximum reach distance points. Initial and final positions of the robot end point on a sample trajectory are seen in Figure 4. The total movement time is decreased until the end point velocity has reached the desired value.

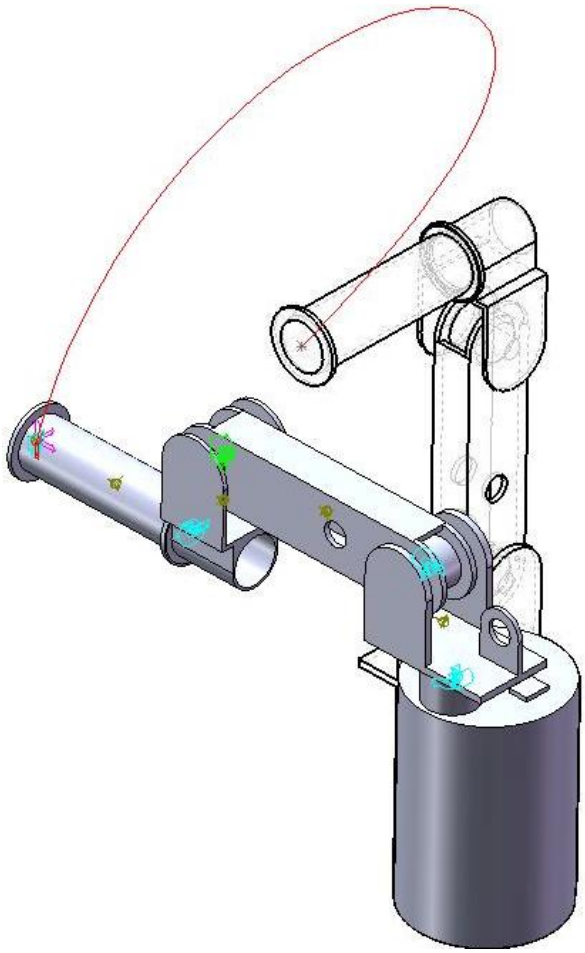


Fig. 3: Initial and end position of the robot on a defined path for the kinematic analysis.

In static/dynamic strain and frequency analysis step finite element model of the robot model is obtained. For this aim, ANSYS has been used for the finite element solutions of this program are very effective. Gravity effects are taken into consideration and the end- point load value is taken as 20 N in the downward direction. The point masses which are equivalent to the masses of the associated motors and gears are added on the robot model. Four- node linear tetrahedral elements are used in the mesh model of the robot parts.

Aluminum materials are assigned to the robot parts without except shafts and rolling element bearing tabs due to lightness. Axes are locked in the static analysis. Motor breaks hold position is similar situation of the static analysis. Static analysis can be repeated for different axes angles by using parametric models of the robot. So stress distribution on the parts of the robot is investigated for different configurations. The static deflection is obtained as 198 µm from the first static analysis in case of the maximum reach distance position of the robot. After changing the parametric dimensions of the robot model, this deflection value is decreased to 77.5 µm. Static displacement distribution for the maximum reach distance position of the robot is seen in Figure 4

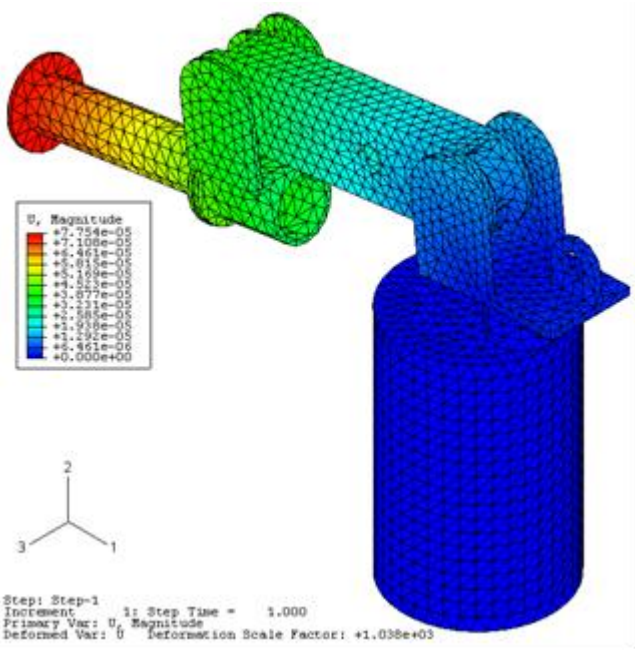
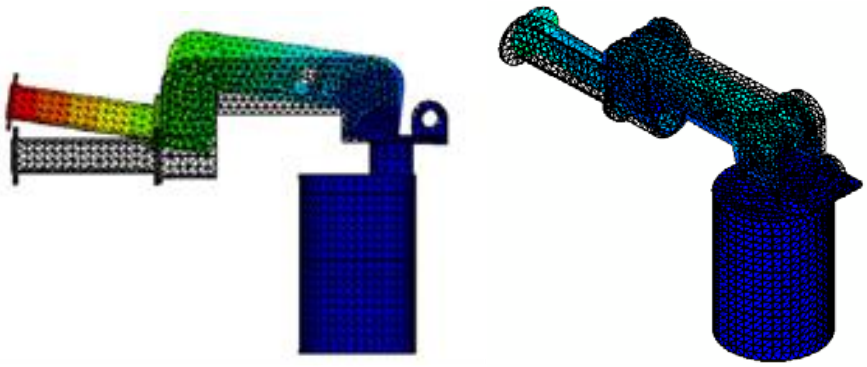


Fig. 4: Displacement results obtained from the final static analysis for the maximum reach distance position.

The natural frequencies of a robot manipulator give information about the manipulator's rigidity. Natural frequencies of the robot are calculated for different positions by using ANSYS. Mode shapes and related natural frequency values of the first three modes for the maximum reach distance position of the robot are seen in Figure 9.



(a) (b)

Fig. 5: Natural frequencies and mode shapes of the robot a) first, b) second.

In the manufacturing process, tolerances between adjacent parts and homocentricity between the axes of the robot are very important. For these reasons especially robot main parts are manufactured by using CNC machines. P1 and P3 parts are manufactured by using 5-axis CNC machine with single fixation. Parts connected to each other by dowel pin.

When all the modifications are finished, the final model of the robot is analysed for pre- defined positions which are position M (maximum reach distance) and position R (reference point, x=200mm, z=200 mm). All the FEM analyses are done in CosmosWorks software.

Figure 6 shows the maximum displacements with 450 N loads to demonstrate 45 kg payload.

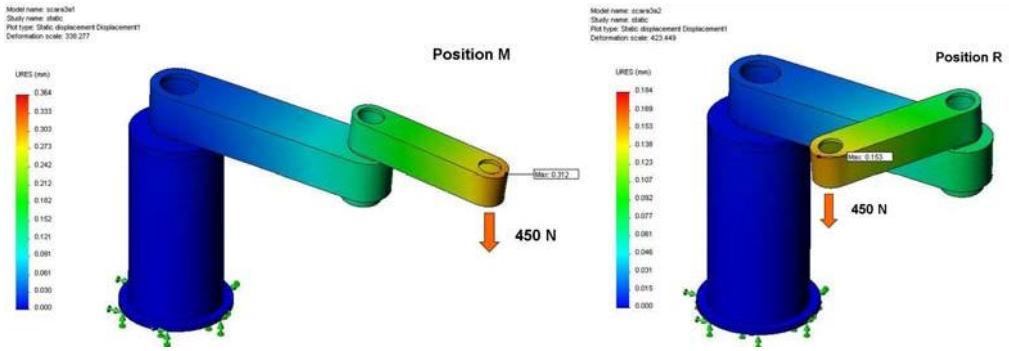


Fig. 6: Displacements of the final model for position M and R (deformation scale: 338 and 423).

With FEM analyses; maximum displacement, maximum stress for Von Mises, equivalent strain and minimum natural frequency of the final robot model are calculated. Table 1 shows the results of analyses for position M and position R. Mesh properties for these FEM analyses are given as followings; mesh type: solid mesh, element size: 17 mm, total nodes: approx. 70.000, total elements: approx. 38.000.

Table 2: FEM Analysis results of the final model for position M and R.

	Position M	Position R
Static Analyses		
Displacement (max.)	0.312 mm	0.153 mm
Stress (Vonmises, max.)	37.238 MPa	36.611 MPa
Strain (Equivalent, max.)	0.000090 ESTRN	0.000086 ESTRN
Natural Frequency Analyses		
1^{st} mode (min.)	31.084 Hz	42.408 Hz
2^{nd} mode	41.643 Hz	61.774 Hz
3^{rd} mode	88.558 Hz	74.358 Hz

When all the simulations and analyses of the robot are finished, 2D drawings are generated. All parts are made from alloy steel material. Alloy steel is preferred because of its high resistance and easiness for manufacturing a part.

Table 3: Comparison of numerical results for the design of the robot.

	Aluminum Design	Composite Design
Maximum Displacement of the End Point (mm)	0.458	0.186
Maximum Von-Misses Stress (N/m^2)	$2.484x10^7$	$1.117x10^7$
First Natural Frequency (Hz)	10.406	27.88
Second Natural Frequency (Hz)	27.732	47.216
Third Natural Frequency (Hz)	61.755	105.34

Evaluation and optimization studies are finished after these results. Detailed design of the robot is constructed and technical drawings are obtained.

The simulated and experimental results are given in tabular form in Table 5.4. As shown from the table the simulated and experimental natural frequencies are well-matched. There are some considerable discrepancies between the numerical and experimental deflection values. These discrepancies are attributed to the assumptions made in the finite element modeling.

Table 4: Comparison of numerical and experimental results of DEU-S45-900.

Position	Comparison Value	FEM	Experimental
M	Static Deflection (mm)	0.380223	0.735
	First Natural Frequency (Hz)	14.828	14.1602
	Second Natural Frequency (Hz)	44.209	43.85
	Third Natural Frequency (Hz)	71.876	70.04
R	Static Deflection (mm)	0.130335	0.345
	First Natural Frequency (Hz)	18.234	17.24
	Second Natural Frequency (Hz)	50.52	54.8
	Third Natural Frequency (Hz)	59.889	66.5

Conclusion:

The present study was made to establish a general rule for the difference in the kinematic and dynamic behavior between the same mechanical element made of aluminum and carbon fibre composite material. Rapid movements of the robot manipulators are necessary to reduce the production times. On the other hand, rapid movement means acceleration and deceleration that cause considerable inertial forces. The importance of the trajectory selection and its effect on the dynamic response is shown by the experimental strain measurements and numerical strain and stress analyses performed for an industrial robot having six-degrees of freedom. The dynamic strain and stress values for an industrial robot can be controlled via proper selection of its trajectory.

The structural behavior of the robot manipulators can be used to compensate the end point deflections from the real target. The numerical results are compared with the results obtained from experimental measurements carried out on DEU-S45-900 robot manipulator. As a result of this comparison, it is seen that the proper definition of the joint flexibilities has great influence on the numerical results. The manufacturers of robot equipment's such as motors and bearings should supply the CAD models of these parts with the same rigidities in order to create the accurate finite element models for precise numerical analyses. Therefore, static and dynamic behavior of the manipulator can be predicted through the numerical analyses. The experimental results presented in this thesis imply that the accurate models for the robot manipulators considered can be established by using today's CAE tools.

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