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Design Optimization of Robotic Arms

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I) Abstract: A robot can be defined as a programmable, self-controlled device consisting of electronic, electrical, and mechanical unit. The elements which are common to all robots can be considered as the basic elements and are as follows:-

- *Manipulator:-*
- *Controller: -*
- *End Effecter: -*
- *Sensors: -*
- *Energy Source: -*

The robot manipulator can be divided into two sections, each with a different function:
Arm and Body and the Wrist -

The current design of the robotic arm consists of manipulators that have been over designed to meet reliability requirements. Hence these manipulators have been designed in a way that they do not make best use of material. They have a low payload to weight ratio. This limits the payload capacity and increases the power requirement for movement of the arms. Attempt has been made to optimize the design of the arms using FEA as a tool. Strength and stiffness have been kept as design criteria while optimizing the weight of the moving arms. The results have shown corresponding reduction in power requirement for arms movement..

\Keywords: Robot, manipulator, topology, optimization,arm,etc

II) PROBLEM DEFINITION:

The most important characteristic of an industrial robot is the weight to maximum payload ratio. The minimization of said ratio can only be achieved by reducing the weight of the robot manipulator. This will also result in increased payload capacity. However this will have to be achieved without severely compromising the static stiffness or the maximum allowable deflection of the individual linkages.

Initially the components were over-designed to meet the reliability requirements. But in today's economy, the weight of industrial robots and its impact on initial and operating cost are of significant concern for both manufacturers and end users.

Hence the components of the robot assembly to be taken into consideration for optimization include

1. The Primary Arm
2. The Secondary Arm

CURRENT SPECIFICATIONS OF ROBOT:

Manipulator Weights –

1. Primary Arm - 3.16 kg
2. Secondary Arm – 4.11 kg

Combined Manipulator weight – 7.27 kg

Rated Payload - 2 kg

III) OPTIMIZATION:

This analysis shall be based on the finite element method (FEM) and consists of completion of the design model using the dimensional data as design variables.

Optimized structural design for the structures of the industrial robots have to meet certain criteria regarding dimensional design and shape, material consumption and adapt this to the functional requirements.

To improve the static and dynamic behaviour of the industrial robot structure, the following requirements must be accomplished:

- Minimum weight structure;
- Maximum static stiffness of structural elements;
- Minimum deformation – Max. precision at the end-effecter.

TOPOLOGICAL OR LANDSCAPE OPTIMIZATION:

Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. Using topology optimization, engineers can find the best concept design that meets the design requirements. Topology optimization has been implemented through the use of finite element methods for the analysis, and optimization techniques based on the method of genetic algorithms, optimality criteria method, and level sets. The topological Optimization using FEM methods for Robotics was employed with shape optimization techniques

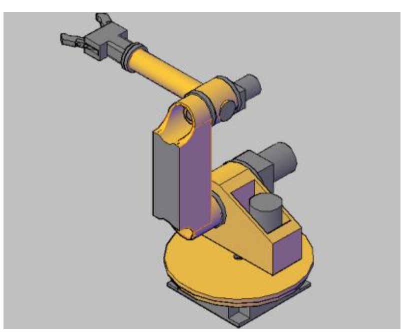

Fig III.1 Visualization of existing robot

INITIAL DESIGN OF PRIMARY ARM:

INITIAL STATUS:

The Primary arm was initially designed using empirical approach. The wall thicknesses were decided based on minimum permissible values for casting process. The box structure was stiffened with the help of a simple cross rib arrangement.

INITIAL STUDIES

For the calculation of initial stresses and deformation in the primary arm the forces acting were calculated.

The forces for analysis are 1) Combined load of the Secondary arm, Secondary arm balancer and secondary arm motor of 98.1 N along the negative Z-axis applied at the face of the upper flange 2) The gravitational force acting globally in the negative Z- axis.

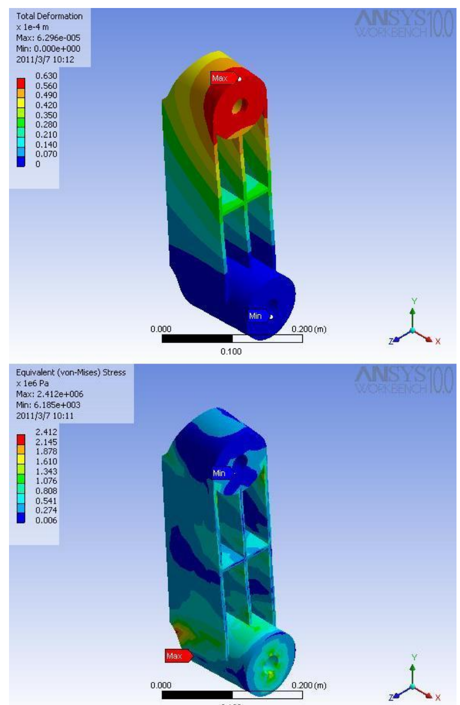

Fig III.2 Results for Initial Design of Primary Arm

Maximum Deformation: 6.296e-005m = 62.96 microns

Maximum Equivalent Stress = 2.412 N/mm^2

INITIAL DESIGN OF SECONDARY ARM:

INITIAL STATUS:

The Secondary arm was initially designed using empirical approach. The cross-section of the arm is circular to account for

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maximum stiffness. The structure is symmetrical across the XY plane.

INITIAL STUDIES

For the calculation of initial stresses and deformation in the primary arm, the forces acting were calculated. The forces for analysis are

The load of the gripper mechanism and the maximum payload of 29.43N along the negative Y-axis applied at the face of the front flange. The gravitational force acting globally in the negative Y-axis.

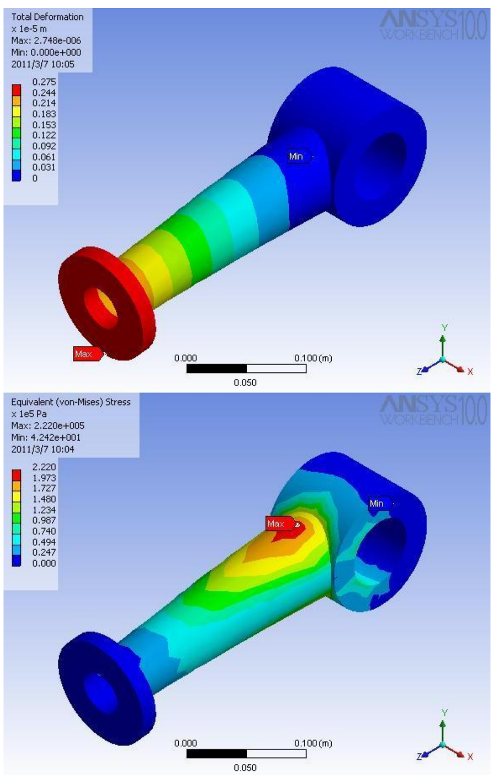

Fig III.3 Results for Initial Design of Secondary Arm

Maximum Deformation: = 2.748 microns

Maximum Equivalent Stress = 0. 222 N/mm^2

TOPOLOGICAL OPIMIZATION

The actual optimization of the primary and secondary arms was done using the Ansys topological optimization routine.

The material used for the initial primary and secondary arms is Al Si 12.The same material is considered for the topological optimization of the primary and secondary arms. The material values for the optimization was set for Aluminum alloy Al Si 12.

Young's Modulus E = 0.675 X 106 N/mm^2

Poisson's Ratio = 0.34

Density = 2710 kg/m^2

PRIMARY ARM OPTIMIZATION:

The basic steps for optimization in Ansys are

Define the structural problem: The optimization model of the primary arm consists of a completely solid structure.

Select the element types: Element type selected is SOLID 95.

Specify optimized and non-optimized regions: The top and bottom flanges are selected as the non-optimized regions while the rest of the structure is selected as the optimized region. Both these regions are given the element type of SOLID 95.

Define and control the load cases or frequency extraction:.

For the primary arm the completely extended position was considered. Forces acting are discussed in initial studies.

The fixed support was given on the face of the bottom flange.

Define and control the optimization process: The mesh size for this given problem is given as 5. This will create elements of equal size so as to facilitate measurement of the optimized shape. Figure shows the mesh of the structure.

The required volume reduction is specified as 50% and the number of iterations given are 50.

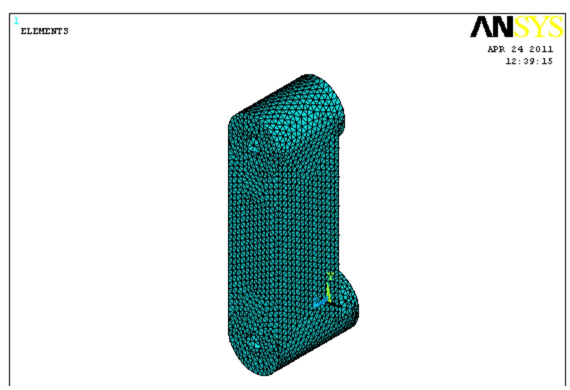

Fig III.4 Mesh of Structural Problem for Primary Arm

REVIEW THE RESULTS:

The results obtained by the optimization routine are as seen the following figure. The blue colour represents material to be removed while the red represents material to be kept.

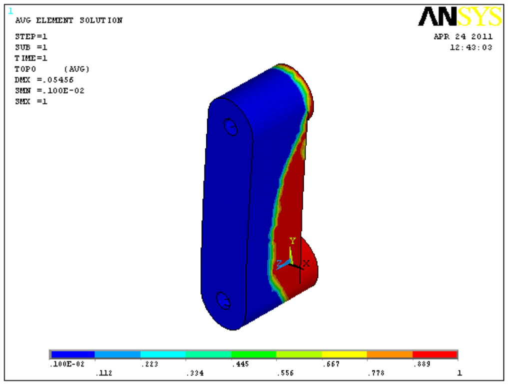

Fig III.5 Optimization for Primary Arm

The result is then refined as to show only the elements that are meant to be kept.

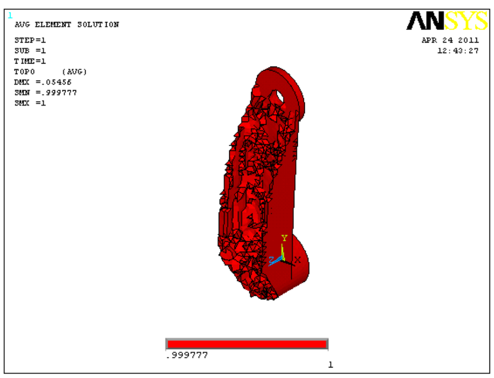

Fig III.6 Result of Optimization for Primary Arm(refined)

CONCLUSIONS DRAWN:

The material at the back of the arm can be removed. The material required to be kept increases gradually as we move from the upper flange to the lower flange. The material at the center of the arm can be removed keeping the side walls intact.

SECONDARY ARM OPTIMIZATION

Similar steps as used for primary arm optimization were used. The optimization model of the primary arm consists of a completely solid structure as shown in the figure.

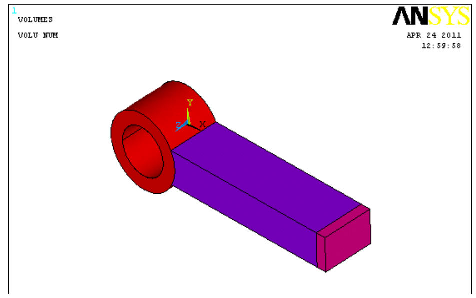

Fig III.7 Structural Problem Definition for Secondary Arm

The element type selected is SOLID 95.

The top and bottom flanges are selected as the non-optimized regions while the rest of the structure is selected as the optimized region. Both these regions are given the element type of SOLID 95.

For the primary arm the completely extended position was considered. Forces acting are discussed in initial studies.

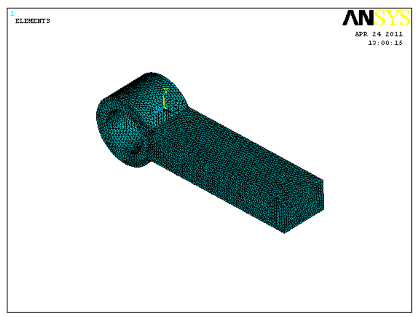

Fig III.8 Mesh Secondary Arm

REVIEW THE RESULTS:

The results obtained by the optimization routine are as seen the following figure. The blue colour represents material to be removed while the red represents material to be kept.

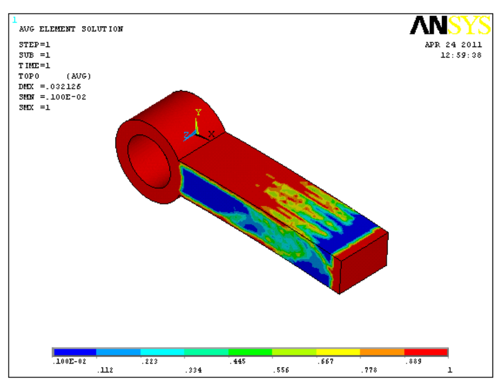

Fig III.9 Optimization for Secondary Arm

The result is then refined as to show only the elements that are meant to be kept.

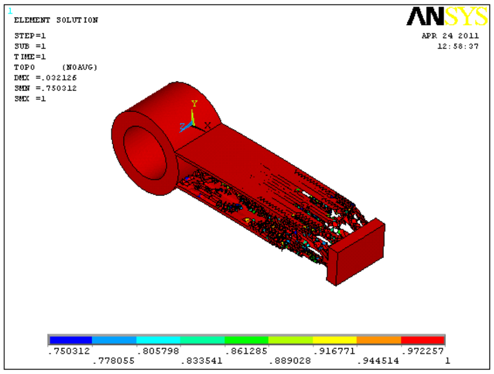

Fig III.10 Result of Optimization for Secondary Arm(refined)

CONCLUSIONS DRAWN:

The proposed section of the secondary arm should be an I section. The arm should taper towards the front while remaining thicker towards the boss side of the arm.

IV) PRIMARY ARM RIBS OPTIMIZATION:

It is has been seen that the thickness of some sections of the primary arm are too large to be manufactured by standard casting process. Hence it has been decided that a front face of the primary arm shall be ribbed for generating a better design. For generating the ribs of the primary arm a 2-D section of the arm shall be considered and same forces shall be applied to it.

An assumption is made that the load is a direct load and not an eccentric load for this optimization process.

The basic steps for optimization used were:

Define the structural problem: The optimization model of the primary arm consists of a 2-D structure as shown in the figure.

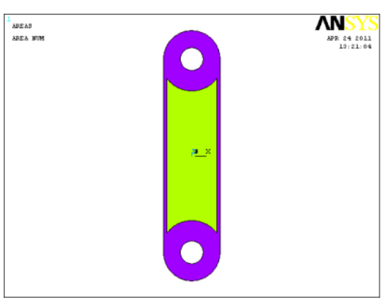

Fig IV.1 Structural Problem Definition for Primary Arm Ribs

The element type selected is PLANE 82.

Specify optimized and non-optimized regions: The top and bottom flanges are selected as the non-optimized regions while the rest of the structure is selected as the optimized region. Both these regions are given the element type of PLANE 82.

Define and control the optimization process:

The mesh size for this given problem is smart size super fine mesh. This will create very small elements which will generate an optimized rib structure for a given problem. Figure shows the mesh of the structure.

The required volume reduction is specified as 70% and the number of iterations give are 50.

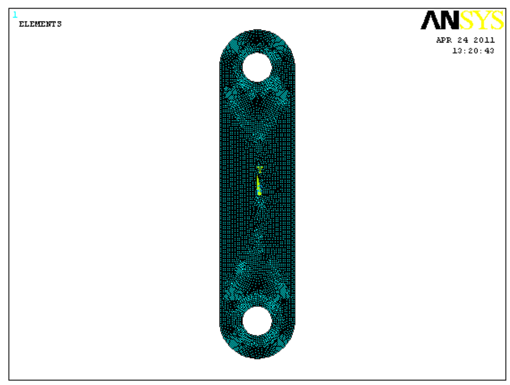

Fig IV.2 Mesh of Structural Problem for Primary Arm Ribs

REVIEW THE RESULTS:

The results obtained by the optimization routine are as seen in the following figure. The blue colour represents material to be removed while the red represents material to be kept.

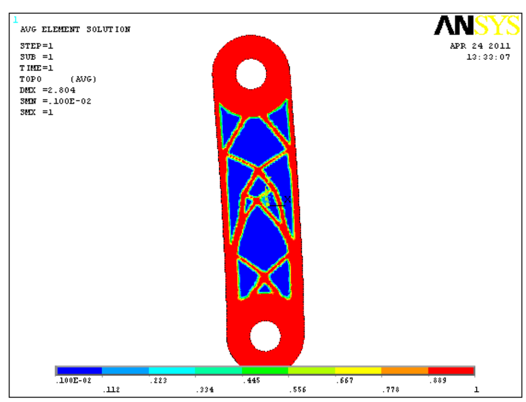

Fig IV.3 Result of Optimization for Primary Arm Ribs

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CONCLUSIONS DRAWN:

This is the approximate shape of the best rib structure for the give element for the given load condition.

The best rib pattern is a cross rib pattern.

The approximate centre of the rib structure should have greater material as compared to the rest of the rib structure.

V) FINAL SHAPES BASED ON OPTIMIZATION RESULTS:

Based on the optimization results the following dimensions for both the primary and secondary arm were finalized. The final shapes were based on the conclusions of the Topological Optimization.

Basic Design considerations like minimum cross-section as well as space for various mountings and electronic components are taken into consideration.

Manufacturing constraints such as limitations in the pattern making process, casting process etc, were also taken into consideration.

Based on these constraints we managed to reach a optimized shape of the two arms. These shapes were then compared with initial shapes and difference in weight was calculated.

There was no real change in the manufacturing process of the initial and final shapes of the primary and secondary arms. However a completely new pattern was required for the casting of the final shapes.

PART NAME: Primary Arm SIZE: 400 X 120 X 100 – 1 No.

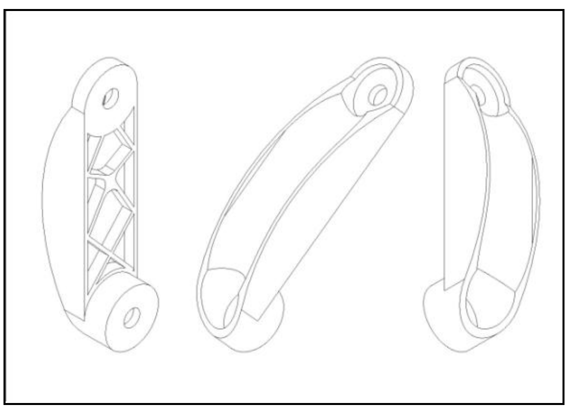


Fig V.1 Final Shape of Primary Arm

PART NAME: Secondary Arm

SIZE: 350 X 100 X 80 – 1 No

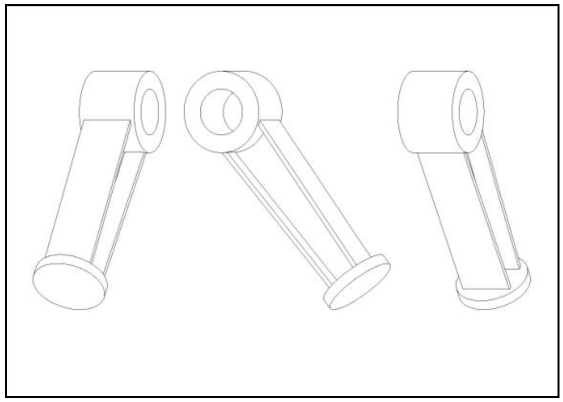


Fig V.2 Final Shape of Secondary Arm

ANALYSIS OF FINAL SHAPES:

The final shapes are analysed so as to ensure that the values of stress and maximum have not increased beyond the previous values.

The analysis of the final shapes shall be done considering the same forces that have been applied for the analysis of the initial shapes. Based on the 3D model, the volume and hence the weight is calculated.

Density of Aluminium Alloy Al Si 12 = 2710 kg/m^2

Arm 2 Initial Volume= 1167385 mm^3

Arm 2 Initial Weight = 1167385 X 2.71 X 10-6 kg = 3.16 kg

Arm 2 Final Volume = 966399 mm^3

Arm 2 Final Weight = 966399 X 2.71 X 10-6 kg = 2.61 kg

Reduction in Weight = 0.55 kg

% Reduction in Weight = 15.23 %

Arm 1 Initial Volume = 1517165 mm^3

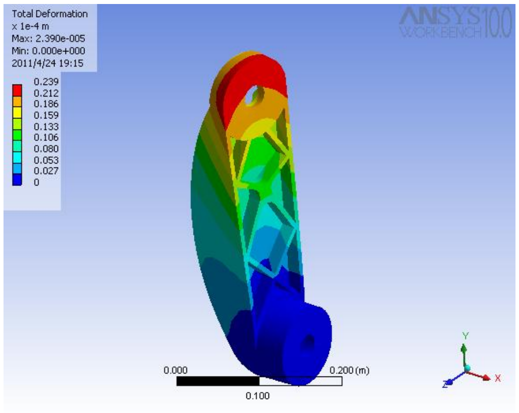
Arm 1 Initial Weight = 1517165 X 2.71 X 10-6 kg = 4.11 kg

Arm 1 Final Volume = 1165229 mm^3

Arm 1 Final Weight = 1165229 X 2.71 X 10-6 kg = 3.15 kg

Reduction in Weight = 0.95 kg

% Reduction in Weight = 23.11 %



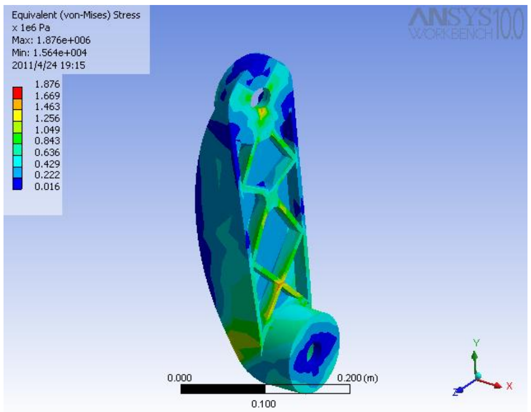
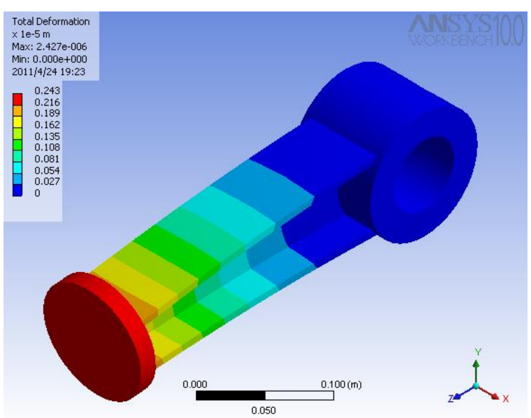


Fig V.3 Analysis of Primary Arm

RESULTS:

Maximum Deformation: 2.390e-005m = 23.9 microns

Maximum Equivalent Stress = 1.876e+006 N/m^2 =1.876 N/mm^2



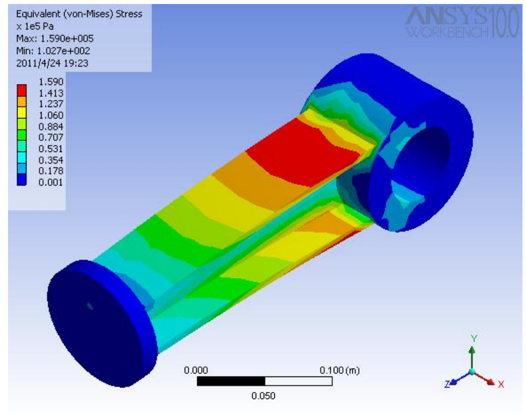


Fig V.4 Analysis of Secondary Arm

RESULTS:

Maximum Deformation: 2.427e-006m = 2.427 microns.

Max. Equivalent Stress = 1.590e+005 N/m^2 =0.159 N/mm^2

ANALYTICAL CALCULATIONS:

In order to guarantee that the optimized design has greater stiffness as compared to initial design the deflection analysis of the initial and optimized shapes is done analytically.

The following assumptions are made in order to simplify the calculations.

The Load acting on both the arms is static load.

The load acting on the arm is acting along the centre of gravity of the arm.

The cross-section of the arm is uniform throughout the length.

The arm is completely fixed at the support end.

CALCULATIONS:

Bending stress and deflection for un-optimized arm I

M.I. = 4.50×10^6 mm^4

Bending moment of load acting at free end of cantilever beam

M = WL = 98.1×340 = 33354 N.mm

Bending stress using flexural formula for pure bending

M/I = σ/y = E/R

Where,

M = Bending Moment

I = Moment of Inertia

σ = Bending stress

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Y = Distance between extreme fibre to neutral axis

E = Young Modulus

R = Radius of curvature

$\sigma = 0.44 \ N/mm^2$

Deflection for cantilever beam

$y = Wl^3 / 3EI = 0.00423$ mm.

Bending stress and deflection for optimized arm I

Moment of inertia = $I_{xx} = 4.54 \times 10^6 \ mm^4$

Bending moment acting at the free end of the cantilever beam

$M = WL = 98.1 \times 340 = 33354$ N.mm

The bending stress using flexural formula for pure bending

$\sigma = MY/I = 0.367 \ N/mm^2$

Calculation for the deflection of cantilever beam

$y = Wl^3/3EI = 0.00420$ mm

Bending stress and deflection for Un-optimized arm II

Moment of inertia , $I = 267.035 \times 103 \ mm^4$

Bending moment acting at the free end of the cantilever beam

$M = WL = 29.43 \times 300 = 8829$ N.mm

Bending stress using flexural formula for pure bending

$\sigma = MY/I = 0.826 \ N/mm^2$

Deflection of cantilever beam

y = 0.01469 mm

Bending stress and deflection for optimized arm II

Moment of Inertia by using parallel axis theorem

M.I. = $452 \times 103 \ mm^4$

Bending moment of load acting at free end of cantilever beam

$M = WL = 29.43 \times 300 = 8829$ N.mm

Bending stress using flexural formula for pure bending

$\sigma = MY/I = 0.488 \ N/mm^2$

Deflection for cantilever beam

y = Wl3/ 3EI = 0.00868 mm

Comparison between Initial and optimized shape deflections

Unoptimized Arm 1 = 0.00423 mm

Optimized Arm 1 = = 0.00420 mm

Unoptimized Arm 2 = 0.01469 mm

Optimized Arm 2 = 0.00868 mm

VALIDATION OF RESULTS:

The effects of optimization have to be checked by implementation of the optimized shapes on the system.

The values of current drawn by the motors for raising the payload are observed.

The graphs of the current drawn by initial design and the current drawn by optimized design are plotted against the payload lifted for both the primary and secondary arm.

For observations on the primary arm the secondary arm is kept in home position and only the primary arm is operated.

It is to be noted that the current drawn by motors for lowering the load did not vary for initial or optimized design.

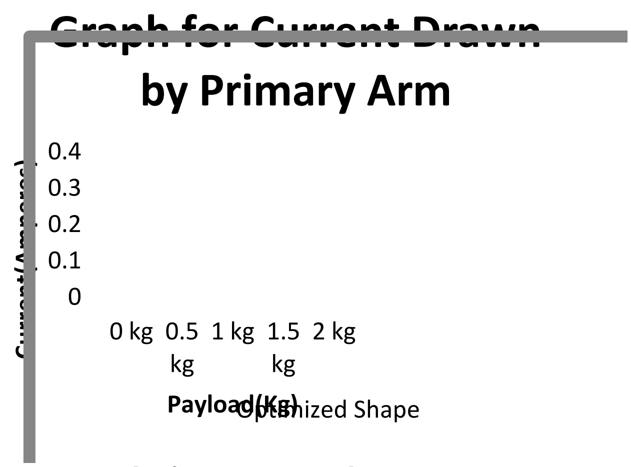

Fig V.5 Graph of Current Drawn by Primary Arm Motor

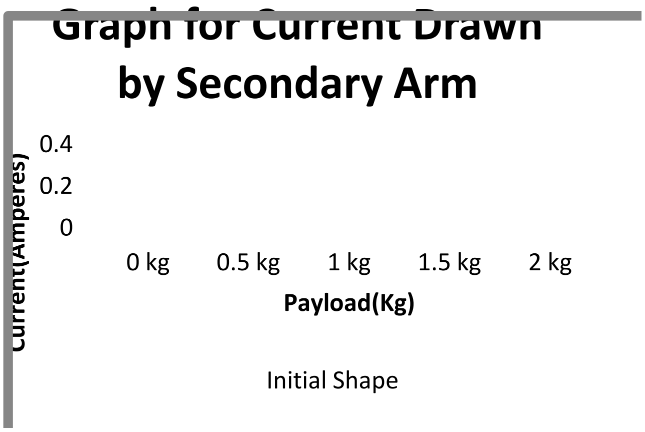

Fig V.6 Graph of Current Drawn by Secondary Arm Motor

CONCLUSION ON OPTIMIZATION:

Hence we can conclude that the final shapes of the primary and secondary arms are lighter in weight than the initial design.

The reduction in weight for Primary arm = 23.11%

The reduction in weight for Secondary arm = 15.23%

The final shapes also have greater stiffness than the initial shapes at the same given loading conditions.

For Primary Arm

Initial design deflection = 62.96 microns

Optimized design deflection = 23.9 microns

For secondary Arm

Initial design deflection = 2.748 microns.

Optimized design deflection = 2.427 microns.

The power required by the motors of the primary and secondary arms is reduced using the optimized design.

CONCLUSIONS:

We succeeded in improving the design of the manipulators and hence reduced their weight.

This also in turn improved the performance characteristics of the robot since less power was required by the motors for the same given payload.

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