Harmonic analysis of wrist mechanism of robot manipulator

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Abstract. Wrist mechanism is a part of robot manipulator which is used to provide the pitch and yaw motions to the end effectors for orienting the loads carried by the end effectors. The wrist mechanism is subjected to different types of vibrations because of the various working conditions. Due to these vibrations wrist mechanism experience higher deformations and stresses; this causes failure of wrist mechanism. It is important to study the dynamic behaviour of the wrist mechanism under different loads before adopting in the application. The structure of the wrist mechanism is modelled in the ANSYS Workbench software and analysed for harmonic loads. Proper boundary conditions, mesh and connections between links & pins are assigned to the wrist mechanism assembly. From the present work, peak deformations of links and pins are occurred at 569.83Hz. Further, the link are analysed with 3D composites those are carbon epoxy and E-glass epoxy. It is observed that carbon epoxy shows better stiffness than E-Glass epoxy and it has weight reduction of 13.76% compared with metals.

Keywords: Robot Manipulator, Harmonic Analysis, ANSYS Workbench, FEM, Wrist Mechanism.

Nomenclature: Link - L, Pin - P, A Peak - Peak Deformation, f- Frequency, φ - Phase Angle.

1. Introduction

Robot plays a vital role in the fields of automobile, aerospace, medical applications etc. With expanding progression in mechanical robots and substitution of the greater part of the work with robots, researchers are working towards an objective of making robots practically like people in each and every angle. Out of the considerable number of parts of the robot, the manipulator plays a main role, in which wrist is the key part to do vital operations like positioning and carrying a load. The wrist mechanism contains motors, links and pins. In the present scenario generally the robots are having bigger wrists mechanisms to give the Pitch and Yaw movements. To overcome this limitation researchers are working towards creating wrist of miniature sizes, in continuation of these endeavors towards creating small scale wrists.
Cheng-Yu Chu [1] proposed one mechanism by motivated from human muscle-tendon activation design and done the static structural and torque analyses on it. Where he studied the strength and stability of the wrist mechanism for static and torque loads. Stefan Staicu [2] built up the recursive relations for kinematics and dynamics of the 3-RRR agile wrist spherical parallel robot are set up. It is controlled by simultaneous torques created from electric motors. The force prerequisite diagrams for each of the three actuators in two computational complexities are resolved. Shaping Bai [3] considered the optimum configuration of spherical parallel manipulators (SPMs) is for an endorsed workspace. To figure out the optimal design, a numerical technique is created for a maximum dexterity. Selc-uk Erkayan [4] stated the investigation of the joint clearance consequences for a welding robot manipulator. In this study only one joint is considered as defective. By the investigation it is understood that the expanded number of joint with clearance makes the kinematic and ‘dynamic performances of the system more regrettable. Hongwei Zhang [5] developed the design, modelling and control of a conservative wrist, which can work in dynamic mode with position or torque control, or passive mode with intuitive force remuneration are talked about to create and check a tracking control algorithm of wrist in dynamic mode. Albert [6] reproduced a machine that can nearly help and cooperate with people. To give the human agreeable appearance and working of the robot with exactness the mechanism is intended to urge unpractised persons to interface with it. Chang Sup Lee [7] expressed the reasonable technique to analyse dynamic characterizes of space robots with joint clearance and upgrades are introduced with enhance the engineering applications.

2. Problem Description

2.1. Statement

To study the response of the wrist mechanism subjected to harmonic loads and to optimize the weight by using 3D composite materials with proper stiffness.

2.2. Problem Modelling

The wrist mechanism is modeled by using proper dimensions [1] in the ANSYS Workbench software.
Figure 4. Pitch Mechanism Dimensions

Figure 5. Yaw Mechanism Dimensions

The dimensions of the pitch and yaw mechanism are listed in the Table 1.

| Pitch Mechanism Dimensions | Yaw Mechanism Dimensions |
|----------------------------|---------------------------|
| \( r_{1p} \)              | 20 mm                     |
| \( r_{2p} \)              | 20 mm                     |
| \( r_{3p} \)              | 65 mm                     |
| \( r_{4p} \)              | \( r_{3p}+D_p \) mm       |
| \( D_p \)                 | 13.9 mm                   |
|                           |                           |
| \( r_{1y} \)              | 30 mm                     |
| \( r_{2y} \)              | 30 mm                     |
| \( r_{3y} \)              | 65 mm                     |
| \( r_{4y} \)              | \( r_{3p}+D_y \) mm       |
|                           | 13.9 mm                   |

2.3. Meshing

Meshing is the process of converting geometry entities to finite element entities [17]. Proper fine mesh and appropriate contact elements are assigned between different parts of assembly for mesh convergence. The meshed model of the wrist mechanism is shown in the Figure 6. Higher order 3-D 20 node element known as solid 186 and higher order tetrahedral 3-D 10 node element known as solid 187 in Ansys software are used for accurate results. The mesh statistics are shown in the Table 2.

| Mesh Statistics          |
|--------------------------|
| Nodes                    | 131702                   |
| Elements                 | 72243                    |

Figure 6. Finite element model of wrist mechanism.

2.4. Connections

Fixed joints are assigned to the motor support, motor casing and base. Revolute joints are assigned between the links and pins. Translation joints are assigned to the actuator of the motors. The typical connections view of the wrist mechanism is shown in the Figure 7.
2.5. Loads and boundary conditions

The loads and boundary conditions are given as per the real working condition [1] and it is shown in the Figure 8. A force of magnitude 222N is applied in the frequency range of 0 to 3000 Hz.

2.6. Material properties

The Material properties are given in the Table 3.

| Material Name                  | Density (kg/m³) | Poisson's Ratio | Young's Modulus (Pa) |
|--------------------------------|-----------------|-----------------|----------------------|
| Aluminum Alloy 6061-T06        | 2700            | 0.33            | 6.9e10               |
| Steel Alloy SKH 09             | 7.85            | 0.30            | 2e5                  |

The parts of the wrist mechanism are assigned with different types of materials as listed in Table 4.

| Part Name                      | Material                  |
|--------------------------------|---------------------------|
| Base, links and motor casing   | Aluminum alloy 6061-T06   |
| Pins                           | Steel alloy SKH 09        |

3. Analysis results

Harmonic analysis uses mode superposition method. For this, modal analysis is required. So the modal analysis is done.
3.1. **Modal Analysis**

In order to obtain the natural frequencies and mode shapes of the wrist mechanism, the modal analysis is done. The first 6 natural frequencies are the basic natural frequencies which have 3 linear and 3 rotational motions. So the 6 natural frequencies are shown in the Table 5.

| Mode No. | Natural Frequency (Hz) |
|----------|------------------------|
| 1        | 500.19                 |
| 2        | 530.94                 |
| 3        | 566.98                 |
| 4        | 569.83                 |
| 5        | 570.06                 |
| 6        | 570.29                 |

The mode shapes of the wrist mechanism are shown in the Figure 9.

![Mode Shapes](image1.png)

**Figure 9.** Mode Shapes

3.2. **Harmonic Analysis**

Harmonic analysis is performed on the wrist mechanism. The frequency response at L01, to the X direction load is shown in the Figure 10 & 11.
From Figure 10 and 11 the peak deformation is occurred as 0.066 mm with a phase angle of -88.85 degrees at a frequency of 569.83 Hz. In this way, the remaining frequency responses for remaining parts are calculated for X directional load and the values are listed in the Table 6.

**Figure 10.** Frequency Vs Amplitude on L 01

**Figure 11.** Frequency Vs Phase angle on L 01

| Link No. | A Peak (mm) | f (Hz) | \( \phi \) (Degrees) | Pin No. | A Peak (mm) | f (Hz) | \( \phi \) (Degrees) |
|----------|-------------|--------|----------------------|---------|-------------|--------|----------------------|
| L 01     | 0.066       | 569.83 | -88.85               | P 01    | 0.144       | 569.83 | -88.85               |
| L 02     | 0.071       | 569.83 | 91.14                | P 02    | 0.084       | 569.83 | 91.14                |
| L 03     | 0.049       | 569.83 | 91.14                | P 03    | 0.054       | 569.83 | 91.14                |
| L 04     | 0.045       | 569.83 | 91.14                | P 04    | 0.045       | 569.83 | 91.14                |
| L 05     | 0.045       | 569.83 | 91.14                | P 05    | 1.265       | 569.83 | 91.14                |
| L 06     | 0.468       | 569.83 | -88.85               | P 06    | 0.044       | 569.83 | -88.85               |
| L 07     | 1.477       | 569.83 | -88.85               | P 07    | 6.213       | 569.83 | -88.85               |
| L 08     | 6.255       | 569.83 | -88.85               | P 08    | 6.356       | 569.83 | -88.85               |
| L 09     | 6.355       | 569.83 | -88.85               |         |             |        |                      |
| L 10     | 6.367       | 569.83 | -88.85               |         |             |        |                      |
From the Table 6, it is observed that the peak deformation is occurred at L 10 and it is occurs at 569.83 Hz.

The frequency response of the wrist mechanism parts to Y-directional load are listed in the Table 7.

| Link No. | $A_{\text{Peak}}$ (mm) | $f$ (Hz) | $\phi$ (Degrees) | Pin No. | $A_{\text{Peak}}$ (mm) | $f$ (Hz) | $\phi$ (Degrees) |
|----------|------------------------|---------|------------------|---------|------------------------|---------|------------------|
| L 01     | 0.0393                 | 569.83  | 91.14            | P 01    | 0.0595                 | 569.83  | 91.14            |
| L 02     | 0.0183                 | 569.83  | 91.14            | P 02    | 0.04131                | 569.83  | 91.14            |
| L 03     | 0.000124               | 569.83  | 91.14            | P 03    | 0.000285               | 569.83  | -88.85           |
| L 04     | 0.00107                | 569.83  | 91.14            | P 04    | 0.000748               | 569.83  | 91.14            |
| L 05     | 0.000187               | 569.83  | 91.14            | P 05    | 1.1342                 | 569.83  | -88.85           |
| L 06     | 0.1908                 | 569.83  | -88.85           | P 06    | 0.56268                | 569.83  | 91.14            |
| L 07     | 0.3848                 | 569.83  | 91.14            | P 07    | 2.3214                 | 569.83  | 91.14            |
| L 08     | 1.00806                | 569.83  | 91.14            | P 08    | 0.013068               | 569.83  | 91.14            |
| L 09     | 0.02049                | 569.83  | 91.14            | P 09    | 0.00018                | 569.83  | -88.85           |
| L 10     | 0.00204                | 569.83  | 91.14            | P 10    | 0.0044                 | 569.83  | -88.85           |

From the Table 7, it is observed that the peak deformation is occurred at P 07 and it is occurs at 569.83 Hz.

The frequency response of the wrist mechanism parts to Z-directional load are listed in the Table 8.

| Link No. | $A_{\text{Peak}}$ (mm) | $f$ (Hz) | $\phi$ (Degrees) | Pin No. | $A_{\text{Peak}}$ (mm) | $f$ (Hz) | $\phi$ (Degrees) |
|----------|------------------------|---------|------------------|---------|------------------------|---------|------------------|
| L 01     | 0.0044                 | 569.83  | -88.85           | P 01    | 0.044                  | 569.83  | -88.85           |
| L 02     | 0.0881                 | 569.83  | -88.85           | P 02    | 0.0422                 | 569.83  | -88.85           |
| L 03     | 0.0323                 | 569.83  | -88.85           | P 03    | 0.0930                 | 569.83  | -88.85           |
| L 04     | 0.00015                | 569.83  | -88.85           | P 04    | 0.00018                | 569.83  | -88.85           |
| L 05     | 2.77E-05               | 569.83  | 91.14            | P 05    | 2.618                  | 569.83  | 91.14            |
| L 06     | 0.524                  | 569.83  | -88.85           | P 06    | 0.286                  | 569.83  | 91.14            |
| L 07     | 1.546                  | 569.83  | -88.85           | P 07    | 0.365                  | 569.83  | 91.14            |
| L 08     | 0.173                  | 569.83  | 91.14            | P 08    | 0.0052                 | 569.83  | -88.85           |
| L 09     | 0.0026                 | 569.83  | -88.85           | P 09    | 0.0008                 | 569.83  | -88.85           |

From the Table 8, it is observed that the peak deformation is occurred at P 06 and it is occurs at 569.83 Hz.
4. Composite Wrist Mechanism

To study the effect of composite materials, Links of the robot manipulator are replaced by 3D composites those are carbon epoxy and E-glass epoxy. The properties of the 3D composite materials [16] are listed in the Table 9.

| Material Name                        | Carbon Epoxy | E-Glass Epoxy |
|--------------------------------------|--------------|---------------|
| Property*                            | 3D Woven fabric |
| Volume Fraction                      | 0.484        | 0.4           |
| Density                              | 1.6          | 1.98          |
| Longitudinal Modulus, E1 (GPa)       | 36.6         | 19.98         |
| Transverse In Plane Modulus, E2 (GPa)| 46.8         | 19.64         |
| Transverse Out Of Plane Modulus, E3 (GPa)| 30.3     | 14.21         |
| Major In Plane Poisson’s Ratio, P12  | 0.04         | 0.204         |
| Out Of Plane Poisson’s Ratio, P23    | 0.289        | 0.312         |
| Out Of Plane Poisson’s Ratio, P31    | 0.21         | 0.288         |
| In Plane Shear Modulus, G12 (GPa)    | 4.9          | 5.8           |
| Out Plane Shear Modulus, G23 (GPa)   | 4.5          | 5.6           |
| Out Plane Shear Modulus, G31 (GPa)   | 4.9          | 5.8           |

4.1. Modal Analysis

The natural frequencies of wrist mechanism using composite materials are shown in the Figure 12.

![Figure 12. Natural frequencies of composite wrist mechanism](image)

From Figure 12, carbon epoxy having higher natural frequencies than the E-Glass Epoxy. Composite materials are having higher natural frequencies than the preliminary materials.
4.2. Harmonic Analysis

The composite wrist mechanism is analysed under Harmonic load in X, Y & Z directions. The peak deformations of wrist mechanism parts are shown in the Figure-13, 14 & 15.

**Figure 13.** Peak deformations of composite wrist mechanism to X directional load

**Figure 14.** Peak deformations of composite wrist mechanism to Y directional load

**Figure 15.** Peak deformations of composite wrist mechanism to Z directional load

From the above figures, it is noticed that, the peak deformations of the wrist mechanism are higher with E-Glass Epoxy than the Carbon epoxy in all directions.
The weight of the wrist mechanism of the robot manipulator using preliminary and composite materials is listed in the Table 10.

| Model                  | Weight (Kg) | % Reduction of weight |
|------------------------|-------------|-----------------------|
| Al Alloy 6061-T6       | 7.898       | --                    |
| Carbon Epoxy           | 6.811       | 13.76%                |
| E-Glass Epoxy          | 7.354       | 6.88%                 |

From Table 10, wrist mechanism using carbon epoxy has lowest weight compared to remaining materials.

5. Conclusions

From this present work peak deformation of the links and pins of the wrist mechanism are calculated. And it is noticed that all the peak deformations which are occurred at 4th natural frequency of the wrist mechanism i.e., 569.83 Hz. Further 3D composites are assigned for the links of the wrist mechanism. The natural frequencies of the wrist mechanism using composite material are higher than the preliminary materials especially Carbon epoxy composite material. The peak deformations of the wrist mechanism using Carbon epoxy are smaller than the E-Glass epoxy. Then Carbon epoxy is recommenced to use that gives a weight reduction of 13.76% compared to metals.

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