

Investigation on Dynamic Performance of Aluminium – Steel Composite Foam based Redundant SCARA Robot



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ABSTRACT: This research examines the effects of foam made of aluminium alloy low carbon (Al-LC) steel on the joint dynamics of Redundant Selective Compliance Articulated Robot Arm (RSCARA). When building a SolidWorks CAD model that incorporates MATLAB/Simscape Multibody, RSCARA components are designed using a customized composite foam material. The dynamic property torque generated at robot joints is determined by simulating the RSCARA system blocks technique using the Simscape Multibody System (SMBS). The use of Aluminium-Low Carbon Composite Metal Foam (AL-LC CMF) in the evolution of RSCARA was shown to be relevant by the dynamic property observations based on the Simscape simulation results.

KEYWORDS: Aluminium alloy-A356, AL-LC CMF, Redundant SCARA, MATLAB, Simscape Multibody, Dynamic property.

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I. INTRODUCTION

The material employed in the structural design of a robot impacts both dynamic and static qualities, such as toughness, rigidity, damping ratio, chemical resistance, and tribological and joint torque properties, among others. In Industry 5.0, the materials play a vital role in developing robots with sustainability and flexibility in manufacturing with enhanced performance. The alloys of metal, aluminium, titanium, and polymer matrix composite materials were used extensively. Robotics engineers frequently use aluminium and its alloy due to their low weight, high strength-to-weight ratio, excellent reliability, and low price. Due to the properties of titanium and 7075 aluminium alloy, which were included into the humanoid robotic joints, the researchers investigated fatigue (Kiyoto et. al, 2013). Similarly, aluminium alloy 6061-T6 was employed to explore the manipulator's performance in the kinetic parts of industrial robot parts and strong corrosion resistance, durability, and affordability (Donald R 2008). Metal foam (MF) has developed due to the fervour with which researchers pursue the creation of novel materials. One special kind of material is metal foam (MF), which is porous, strong, and has a particular stiffness-to-weight ratio. It also has a large absorption capacity and high energy storage. Despite impairing mechanical performance, these materials are appealing for various structural applications, including those for spacecraft,

vehicles, ballistic armour, etc. (Degischer & Kriszt, 2002). Compared to other foam-type materials (such as thermoplastic foam), metal foams are favoured for tough and high-temperature settings because of their melting temperature, which is comparable to that of the matrix material (Ashby et. al, 2000, Rabiei & Vendra, 2009, Sugimura et. al, 1997, Lim et. al, 2002, Mahadev et. al, 2023).

To create the novel composites-based metal foam (CMF) materials, hollowed metal matrix spheres had interstitial voids that needed to be filled. This CMF hollowed sphere offers a homogenous cell size and shape that is correct, and the matrix material will strengthen weak cell walls and ensure good bonding between the spheres. The structural and absorption qualities are improved (Kupp et. al, 2001, Neville & Rabiei, 2008, Brown et. al, 2010, Patel R., Shadpey F 2005, Petrov P. 2018). Now a days Aluminium-Low Carbon steel composite foam Aluminium–Low Carbon Composite Metal Foam (Al-LC-CMF) is an adaptable material that associates with the objectives of Industry 5.0 by supporting sustainable and enabling flexible manufacturing process. Al-LC-CMF is applicable high energy absorption applications and so several research works are carried out in this area in the recent years (Neville & Rabiei, 2008, Fisseha Zewdie et. al, 2024). These improved material characteristics drove researchers to investigate how Al-LC-CMF impacted the dynamic characteristics of the Redundant (R) SCARA configuration

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robot (Fig. 1). The affordable robotic manipulator SCARA has one prismatic joint and two revolving joints. Aluminium makes up the standard SCARA robotics manipulator components with agility. It is implemented for light-duty operations like stacking electronics components, product inspection, handling of materials, etc. In contrast to non-redundant SCARA, RSCARA is agile and capable of various tasks (Brown et. al, 2010). In the recent SCARA research works, the focus is on energy utilization, positioning control and redundancy. So if an advanced simulation methodology is adapted as mentioned in the following sections, robot with suitability to industry 5.0 can be made to serve the respective industrial growth.

This present research study employed SolidWorks and MATLAB/Simscape Multibody tools to evaluate the performance of the recently proposed Al-LC (aluminium - low carbon) CMF material and A356 aluminium alloy in Prismatic Revolute Revolute Prismatic (PRRP) PRRP configuration RSCARA. It is an outstanding effort that any robotic engineers have ever suggested. It is necessary to evaluate a SCARA robot's performance virtually utilizing a modelling and simulation environment before performing a real-world operation (Patel & Shadpey, 2005). Many researchers used MATLAB, among various simulation platforms (Lakshmi et. al, 2007) Mashagbeh M. A 2015). MATLAB simulations have been used to anticipate space and joint coordinates, monitor trajectories, energy optimal path planning and investigate the actuator dynamics of Redundant SCARA (Mashagbeh et al, 2015, Petrov, 2018, Mrak, et. al, 2023, Urrea & Kern, 2015, Crenganis et. al, 2021). The physical model simulation environment coupled with sound modelling methodologies found in MATLAB/Simscape Multibody is preferred by researchers over the MATLAB/graphical Simulink development platform when analysing the dynamic features of SCARA (Thong Duc Hong 2024). SimMechanics simulation has already been used to study the performance and trajectory of 6 DOF Spatial Parallel Robot (SPR) SPR, Wheeled Robot, humanoid, 2L Planar Robot, Parallel Robot (RRR Configuration), 3 DOF Revolute Prismatic Spherical (RPS), and SCARA (Uk et. al, 2020, Alshamasin et. al, 2018, Agbo et. al, 2021, Gouasmi et. al, 2012, Yu et. al, 2010, Hanchen et. al, 2009, Matoui et. al, 2018, Deliktaş et al 2023). To simulate the route and motion characteristics of six axis industrial robot KUKA KR5 robot KUKA KR5 applied for insertion using MATLAB/SimMechanics (Udai et. al, 2011). Similarly, SimMechanics was used to create and simulate an industrial spot-welding robot prototype (Gang et. al, 2010). Using SolidWorks, a powerful 3D CAD modelling programme, and the MATLAB Simscape add-on tools, improves robotic systems' creation. To analyze its four degrees of freedom (DOF) palletizing industrial robot applicable in the tea industry SolidWorks modelling and SMBS were utilized. A physical model of the mobile manipulator system's dynamic behaviour was examined using SolidWorks/Simscape multibody co-simulation (Mezui, et al, 2023).

In a recent study, the computed torque control system was evaluated using the digital twin model of a six-DOF articulated robot created with Simscape Multibody (Boschetti, & Sinico, 2024). Bruzzone, et, 2024 conducted the research work to

reduce energy consumption SCARA-like manipulator in pick-and-place tasks using Simscape Multibody simulation.

Aluminium alloys make up the standard design material for SCARA robot manipulator components with agility. The titanium alloys are also a design material for robot for its, corrosion resistance and strength-to-weight ratio. But comparing with aluminium its cost is high. In this work the impact of Al-LC steel composite foam on the design of redundant SCARA robots in three stages was investigated. Using the SolidWorks software's modelling capabilities and the identified material property properties of the CMF material, the first stage was building the 3D CAD RSCARA. In the second stage, the kinematic modelling was done using the CAD Model using Denavit-Hartenberg (D-H) method to determine the tool position during the robotic manipulation to perform the drilling task. 3D CAD solid model was transferred to the Simscape Multibody II gen. simulation environment to generate the multi-body system block diagram (MBSBD) of RSCARA was done as the third stage. In the last stage, Simscape simulation is used to obtain the torque applied to the joints.

II. MATERIALS AND MODELLING

The use of Al-LC steel composite foam as an effective replacement for the structural design of RSCARA to enhance the dynamic efficiency with reduction in overall weight is a novel feature of this proposed research work. The 3D CAD model of RSCARA with Multiple Tool End Effector (MTEE) MTEE is developed as a first phase of this research work methodology with the modelling capability of SolidWorks software as presented in Fig.1. The attributes of selected material A356 and Al-LC steel composite foam, are assigned to RSCARA components such as main arm, forearm, prismatic arm and tool holder Main arm, Forearm, Prismatic arm and tool holder in the modelling phase. In Fig. 1, the D-H parameters and the respective dimensions are as follows: The main arm length (lm) = 300mm, forearm length (lf)= 300mm, drilling arm length for Tool A and Tool B is -Z3 (la) =100mm, drilling arm length for Tool B is -Z3, (lb)= 100mm, Revolute joints 1,2 (J1 & J2) . The offset link length d1 = 300mm, d2 = 0, d3 = 0, d4 = 5mm-300mm, d5 = d6 = 80mm = 80mm, d6 = 80mm. The material properties for Al alloy A356 and AL-LC CMF were highlighted in table 1, respectively. The RSCARA simulated Simscape's multibody platform via a design platform link after the modelling phase.

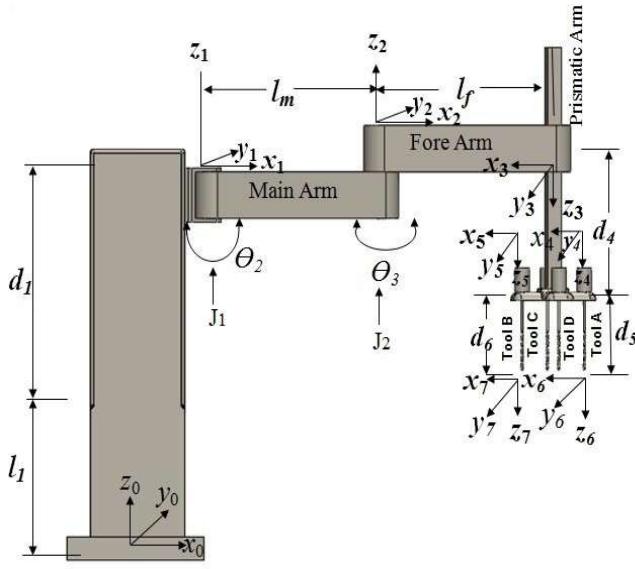


Fig. 1 3D CAD representation of RSCARA with axis convention

III. KINEMATIC DESIGN

The proposed RSCARA is equipped with multiple tools; to position the tool with proper orientation, the kinematic modelling is very vital to determine the tool position. The kinematic design of the suggested RSCARA is developed using the Denavit-Hartenberg (D-H) method. Joint variables were used to determine the robotic manipulator's position and orientation. Equation (1) illustrates how the homogeneous transformation matrix A_i represents the end effector's location and orientation.

$$A_i = T(z, d) T(z, \theta) T(x, a) T(x, \alpha) \quad (1)$$

$$A_i = \begin{bmatrix} R_i^{i-1} & O_i^{i-1} \\ 0 & 1 \end{bmatrix} \quad (2)$$

$$A_i = \begin{bmatrix} \cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Where as in the Equation (3), Link length (a_i), Twist angle(α_i), Link offset (d_i), Joint angle (Θ_i).

By substituting D-H parameters given in the Table 1 in Equation (4), the 4×4 matrices of $A_1, A_2, A_3, A_4, A_5, A_6, A_7$ was derived.

Table 1. D-H parameters of the redundant SCARA robot

Axis number	Link length(a_i)	Link offset (d_i)	Twist angle(α_i)	Joint angle (Θ_i)
1	0	$l_p + d_1$	0	0
2	l_m	0	0	Θ_2
3	l_f	0	180°	Θ_3
4	l_a	d_4	0	0
5	l_b	d_4	0	0
6	0	d_5	0	Θ_6
7	0	d_6	0	Θ_7

The Tool A position is achieved by applying Equations (4) and (5).

$$T_A = A_1 A_2 A_3 A_4 A_6. \quad (4)$$

$$T_A = \begin{bmatrix} C_6 C_{23} + S_6 S_{23} & -S_6 C_{23} + C_6 S_{23} & 0 & (l_a + l_f) C_{23} + l_m C_2 \\ C_6 S_{23} - S_6 C_{23} & -S_6 S_{23} - C_6 C_{23} & 0 & (l_a + l_f) S_{23} + l_m S_2 \\ 0 & 0 & -1 & d_1 + l_p - d_5 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

The Tool A Position is (X_A, Y_A, Z_A) given in the Equation (6)

$$x_A, y_A, z_A = (l_a + l_f) C_{23} + l_m C_2, (l_a + l_f) S_{23} + l_m S_2, d_1 + l_p - d_5 - d_4 \quad (6)$$

In the matrix Equations (5) and (8) $C_2, C_3, C_6, C_7, S_2, S_3, S_6, S_7$ represents the Cosine and sine function of joint angles.

The Tool B position and orientation are achieved by applying Equations (7) and (8).

$$T_B = A_1, A_2, A_3, A_5, A_7 \quad (7)$$

$$T_B = \begin{bmatrix} C_7 C_{23} + S_7 S_{23} & -S_7 C_{23} + C_7 S_{23} & 0 & (l_f - l_b) C_{23} + l_m C_2 \\ C_7 S_{23} - S_7 C_{23} & -S_7 S_{23} - C_7 C_{23} & 0 & (l_f - l_b) S_{23} + l_m S_2 \\ 0 & 0 & -1 & d_1 + l_p - d_6 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

(X_B, Y_B, Z_B) is the Tool B position given in the Equation (9).

$$x_B, y_B, z_B = (l_f - l_b) C_{23} + l_m C_2, (l_f - l_b) S_{23} + l_m S_2, d_1 + l_p - d_6 - d_4 \quad (9)$$

Whereas $C_{23} = \cos(\Theta_2 + \Theta_3)$, $S_{23} = \sin(\Theta_2 + \Theta_3)$

Equation (10) was utilized to determine the location of drilling tools C and D by utilizing the midpoint coordinate position 'M' of the tool head through the D-H representation.

$$x_M, y_M, z_M = (l_f C_{23} + l_m C_2, l_f S_{23} + l_m S_2, l_p + d_1 - d_4 - d_M) \quad (10)$$

Here $d_M = d_5 = d_6$

The Tool C and Tool D position are predicted by referring right angle triangle principle in the Geometrical construction of robotic manipulator given in the Figure 8.

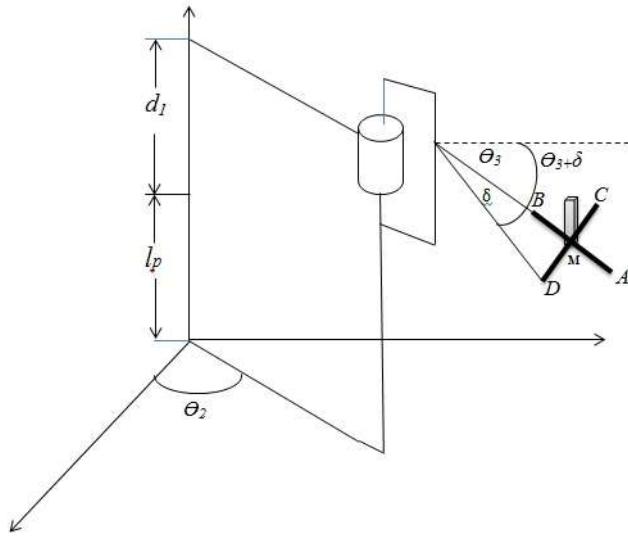


Fig. 2 Geometrical representation of the SCARA with MTEE

The tool C position can be obtained by the geometrical illustration in the Figure 2, by applying the value $\Theta_3 = \Theta_3 - \delta$ in the Equation (11).

$$x_C, y_C, z_C = (l_f C_{23} + l_m C_2, l_f S_{23} + l_m S_2, l_p + d_1 - d_4 - d_M) \quad (11)$$

Here $d_M = d_5 = d_6$, $S_{23} = \sin(\Theta_2 + \Theta_3)$, $C_{23} = \cos(\Theta_2 + \Theta_3)$,

Likewise, by substituting $\Theta_3 = \Theta_3 + \delta$ in the Eq. (12), the Tool D position can be obtained

Material used	Density (g/cm ³)	Young's modulus (Gpa)	Tensile Strength (Mpa)	Poisson's ratio	Shear modulus (Gpa)
A356	2.67	36.17	165	0.31	27.20
Aluminum - LC Steel composite metal foam	2.41	30	185	0.33	22.38

$$x_D, y_D, z_D = (l_f C_{23} + l_m C_2, l_f S_{23} + l_m S_2, l_p + d_1 - d_4 - d_M) \quad (12)$$

The design of the proposed RSCARA was based on the D-H parameters.

The customised material given in the Table 2 was assigned in the CAD model for further simulation process to identify the joint dynamic characteristics.

Table 2. Material Properties used for Simulation (Neville B.P 2008).

IV. SIMSCAPE MULTIBODY SYSTEM (SMBS) AND SIMULATION

SMBS simulation software is a MATLAB add-on tool that can develop and simulate 3D electromechanical systems (Saravana Mohan et al, 2023, Udai et. al, 2011, Gang et. al, 2010, Fedak & Durovsky, 2014). It is competent in modifying the design structure by varying the constraints and getting the results in minimal time. The sequence of blocks of SMBS depicts the entities like rigid bodies, joints and force elements as shown in Fig.3 and 4. The exporting features of SolidWorks obtain the XML file of RSCARA from CAD model. It was executed in MATLAB/Simscape environment to form a multibody system MATLAB/Simscape environment to develop a multibody system block of the proposed robot.

V. SIMSCAPE SIMULATION RESULTS

The Sine wave, Simulink convertor, PS - Simulink-PS, and joint blocks of the SMBS of RSCARA are allotted the I/O joint parameters in accordance. In 10 seconds, simout blocks can detect joint torque for 900 angular displacements. The revolute joint primitives are assigned as shown in the Fig. 5 and 6. The graphical output figure of the robot and joint with location of composite material from simscape simulation is shown in Fig. 7.

The development of Time vs Torque charts, as seen in Figs. 7 (a and b) and 8 (a and b), allow the mechanic's explorer to track the Simulation. Fig. 4's graphical representation of the torque happening in the joints as seen during the Simscape Multibody simulation. If the robot's components are made of the aluminium alloy A356, the torque at joints 1 and 2 is 76.3 Nm and 61.23 Nm, respectively, as shown in Fig. 7. The torque values determined by Simulation are 68.55Nm and 55.5Nm at the joints 1, 2, if AL-LC CMF is applied to the SCARA manipulator links, as illustrated in Fig. 8.

The simulation findings suggest that if AL-LC CMF is used as the design material, the torque acting in the RSCARA joints is comparatively more minor (CMF). The homogeneous hollow sphere created by precise cell size and shape in the CMF material gives it unique attributes like damping ratio, strong compression strength, low density, and high energy absorption rate. So, AL-LC CMF material is preferable for RSCARA design. In connection with the obtained simulation results, the major limitation is the change in material properties based on the selection of manufacturing methods and controlling parametric conditions.

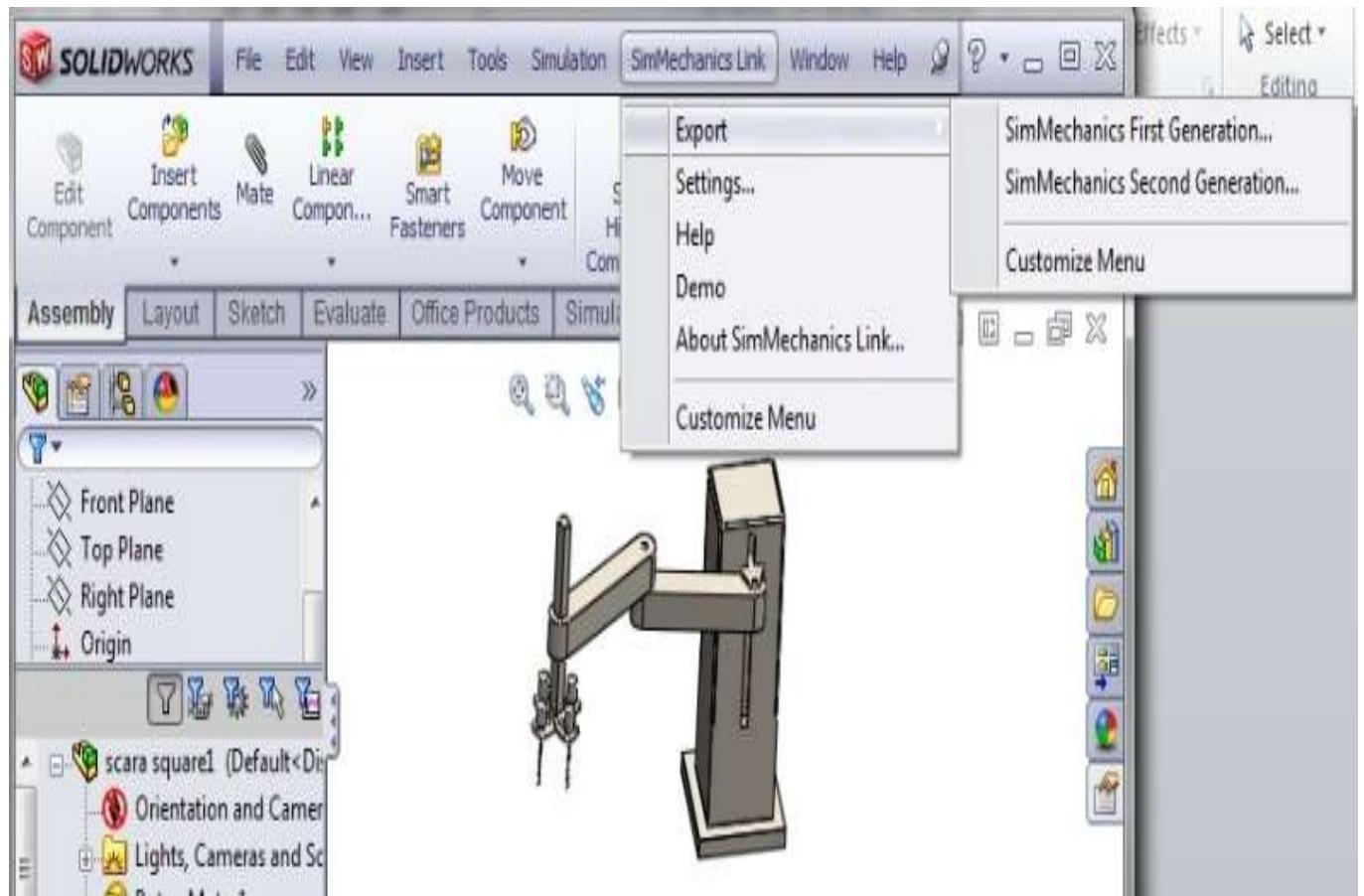


Fig. 3 3D CAD model of proposed SCARA exported from Solid works environment

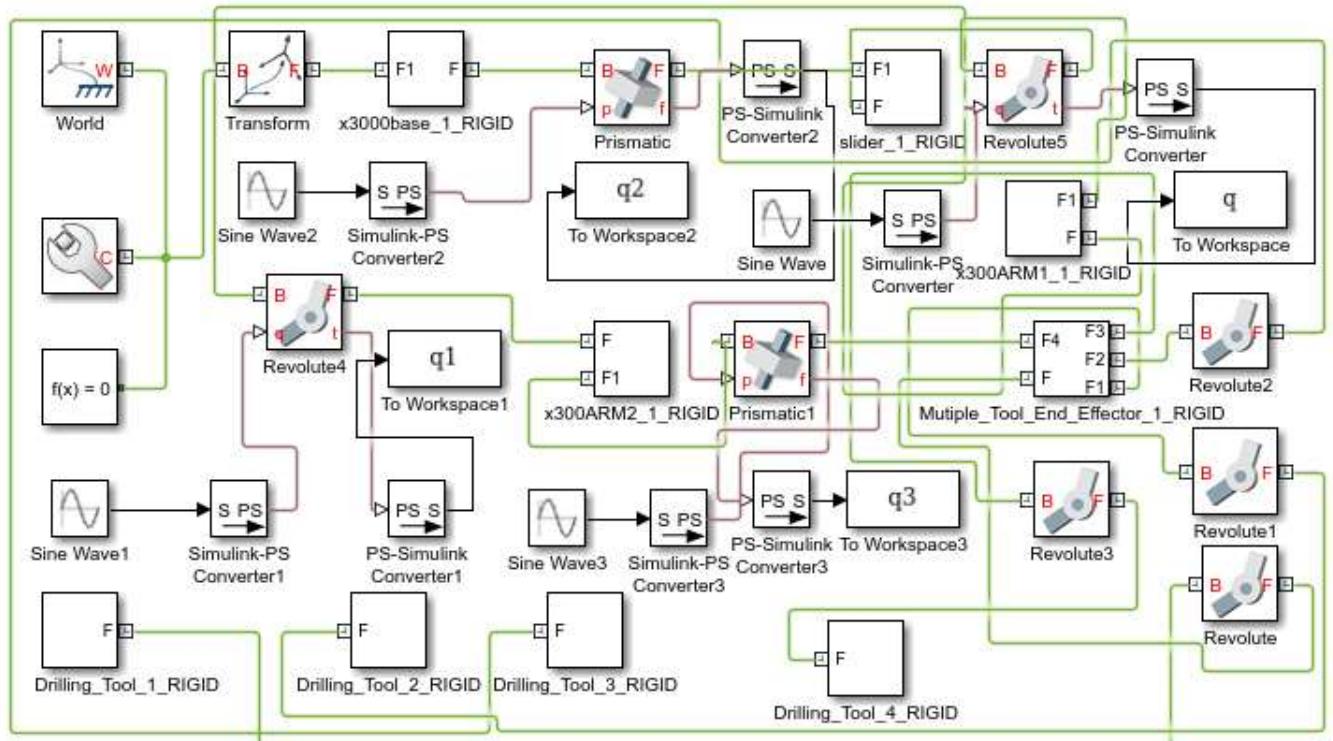


Fig. 4 Generated Simscape Multibody system blocks of RSCARA

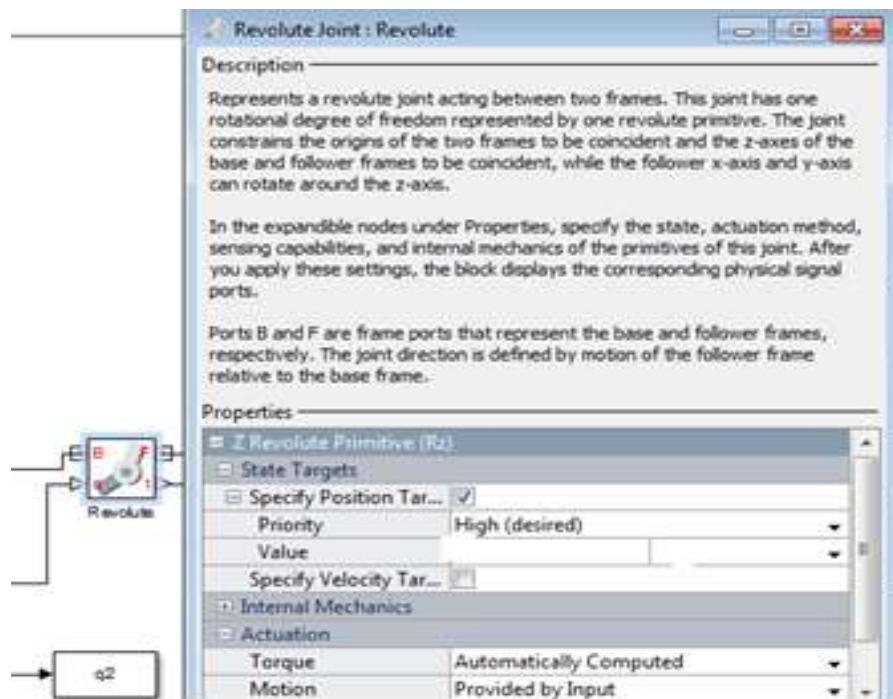


Fig. 5 Assigning joint primitives to the simscape blocks for actuation

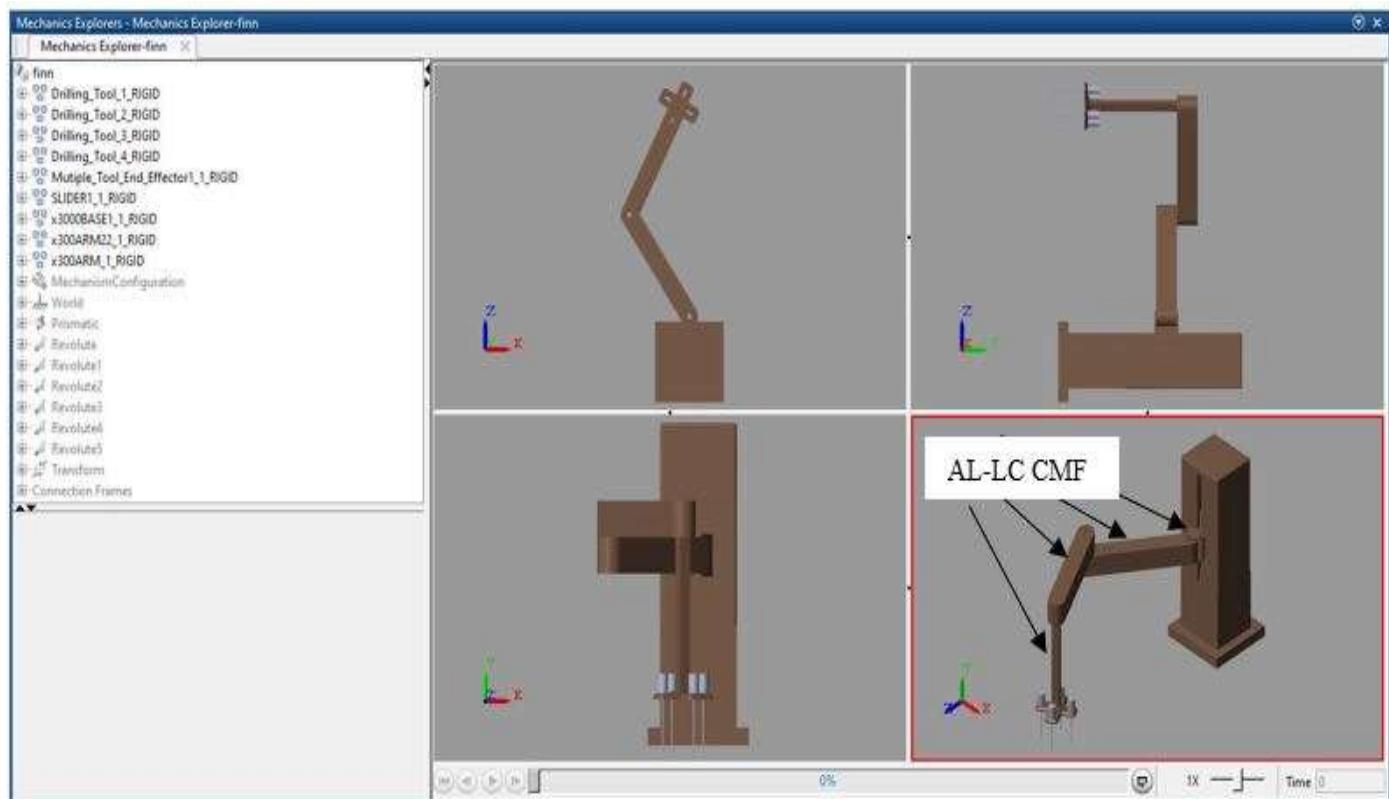


Fig. 6 A graphical output figure of the robot and joint with location of composite material from simscape simulation

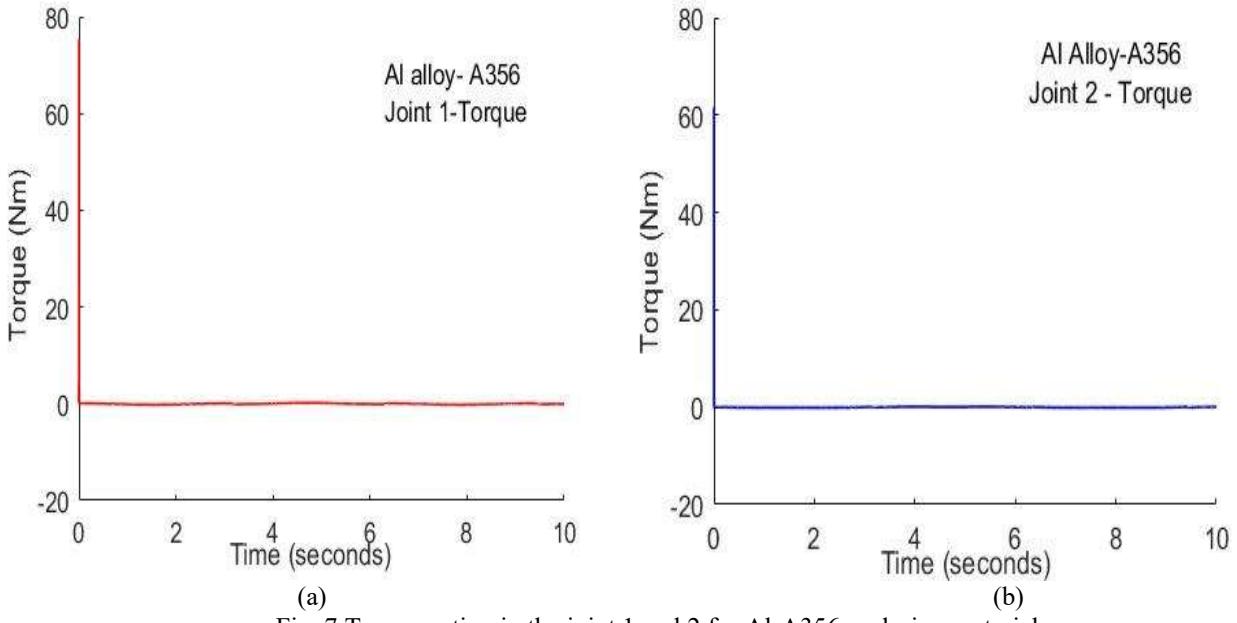


Fig. 7 Torque acting in the joint 1 and 2 for Al-A356 as design material.

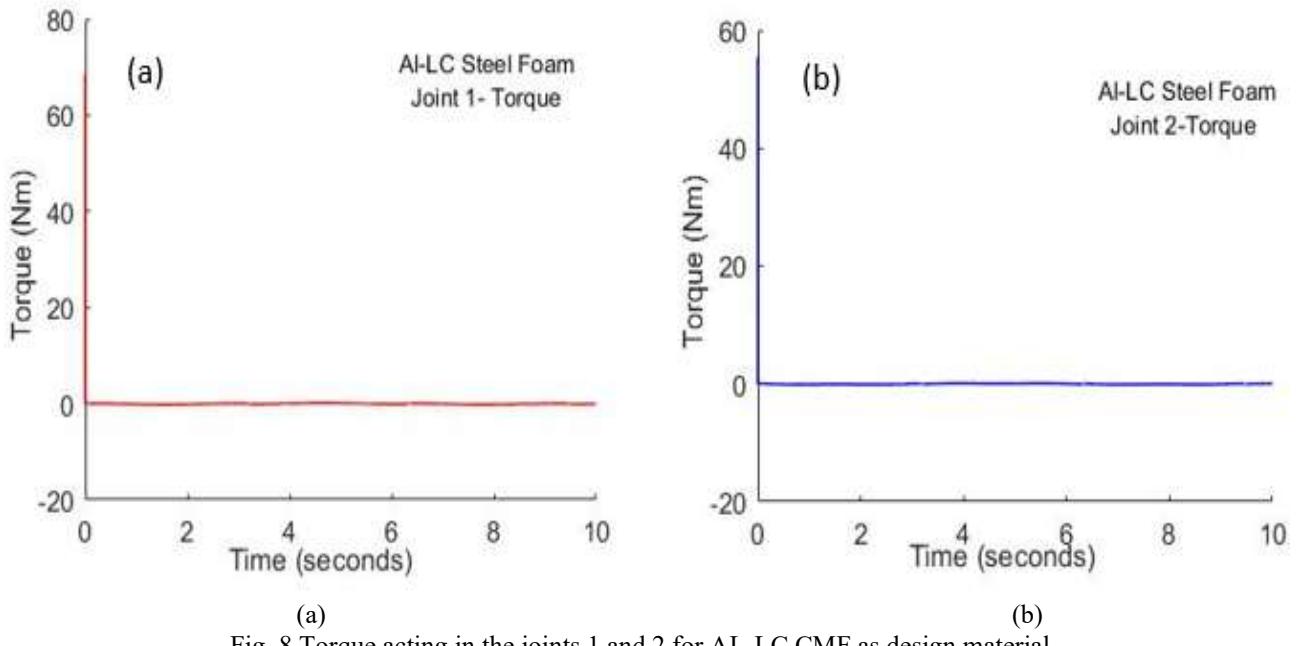


Fig. 8 Torque acting in the joints 1 and 2 for AL-LC CMF as design material.

IV. CONCLUSION

The impact of AL-LC CMF on the joint dynamic characteristics of RSCARA is investigated in this proposed research study utilizing multibody simulation methodology. The dynamic property torque operating in the joints was observed by designating A356 and AL-LC CMF as the design materials for the main arm, forearm, prismatic arm, and tool holder of the newly configured RSCARA. According to simulation outcomes results obtained, torque at joints 1 and 2 is

comparatively less while using AL-LC CMF than aluminium alloy A356 in RSCARA. This method paves the way for the future application of AL-LC CMF in the development of other robot configurations that have higher mechanical stability and lower costs.

AUTHOR CONTRIBUTIONS

M. Saravana Mohan, P.S. Samuel Ratna Kumar: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Chithirai Pon Selvan, P.M. Mashinini, Ghani Sikkandhar Thanish:** Supervision, Writing – original draft, Writing – review & editing. **Swaroop Ramaswamy Pillai, Kahtan Aziz:** Writing – review & editing.

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