Journal of Engineering Mechanics and Machinery (2026)
Clausius Scientific Press, Canada

DOI: 10.23977/jemm.2026.110206
ISSN 2371-9133 Vol. 11 Num. 2

Analysis of Manipulator Motion Performance Based on Numerical Simulation and Intelligent Path Planning Algorithm

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Keywords: SCARA robotic arm; Finite element analysis; Path planning; Motion performance; Obstacle avoidance control

Abstract: To address issues such as vibration, trajectory irregularity, and insufficient motion stability in four-degree-of-freedom SCARA manipulators under high-speed operation, this paper proposes a comprehensive motion performance analysis method combining finite element numerical simulation with path planning algorithms. Using a four-degree-of-freedom SCARA manipulator as the research object, an ANSYS Workbench-based finite element model was established to conduct static, modal, and harmonic response analyses, evaluating structural strength, stiffness, and dynamic stability. A MATLAB-based kinematic model of the manipulator was developed, employing the PCHIP piecewise cubic interpolation method to design smooth obstacle-avoidance paths in static obstacle environments, followed by motion simulation validation. Results indicate: the manipulator exhibits a maximum equivalent stress of 216 MPa, maximum end deformation of 0.13 mm, and a first-order natural frequency of 54.04 Hz, showing no significant resonance response under periodic excitation, meeting strength and dynamic stability requirements. The proposed path planning method generates continuous smooth trajectories, achieving safe obstacle avoidance and stable tracking. The study achieves coordinated evaluation of path planning and structural performance, providing theoretical foundations and technical references for the engineering application and optimal design of SCARA manipulators.

1. Introduction

Against the backdrop of rapid development in intelligent manufacturing and industrial automation, industrial robots have become the core equipment of modern manufacturing systems. Among them, robotic arms are widely used in fields such as assembly, handling, welding, sorting, and precision machining due to their high efficiency, high repeatability positioning accuracy, and strong environmental adaptability. With the development of industrial production towards high-speed, intelligent, and high-precision directions, higher requirements have been put forward for the motion performance of robotic arms. It not only requires robotic arms to be able to complete path planning and obstacle avoidance tasks, but also requires them to have good structural stability and dynamic response performance [1].

The SCARA (Selective Compliance Assembly Robot Arm) robotic arm has the advantages of compact structure, high-speed planar motion, high stiffness, and excellent repeatability positioning accuracy, and is widely used in electronic assembly, automatic handling, and industrial sorting scenarios [2]. However, due to its typical cantilever structure characteristics, it is easily affected by factors such as inertial loads, periodic excitations, and structural flexibility during high-speed operation or complex trajectory tracking, resulting in structural vibration and dynamic deformation, which in turn affects positioning accuracy and operational stability [3].

Therefore, studying the motion problem of robotic arms solely from the perspective of path planning is no longer sufficient to meet the requirements of engineering applications. The motion performance of a robotic arm depends not only on the rationality of the path planning algorithm, but also on the combined effects of structural strength, stiffness, and dynamic stability. Combining path planning algorithms with finite element numerical simulation analysis to comprehensively study the motion performance of robotic arms has important theoretical significance and engineering application value.

In the field of robotic arm path planning, foreign research started earlier. Khatib first proposed the Artificial Potential Field (APF) method in 1986, which achieved real-time obstacle avoidance control for robots by constructing a target attraction potential field and an obstacle repulsion potential field, laying an important theoretical foundation for path planning research [4]. Due to its advantages of simple computation, strong real-time performance, and easy implementation, the APF method is widely used in local path planning problems for industrial robots. However, traditional APF methods still suffer from problems such as local minima, unreachable targets, and path oscillations near obstacles [5].

With the continuous deepening of research, foreign scholars are gradually combining optimization algorithms with path planning methods to improve the quality of path planning and motion stability. For example, Particle Swarm Optimization (PSO) algorithm is widely used in robot path optimization research due to its strong global search ability, simple parameter settings, and fast convergence speed [6]. In addition, Fast Random Tree (RRT), A * algorithm, and hybrid planning methods have also been applied in complex environment path planning to improve path smoothness and obstacle avoidance efficiency [7].

With the development of industrial robots towards high-speed and lightweight direction, the research focus abroad has gradually expanded from "path accessibility" to "motion performance optimization". The robotic arm may be affected by inertial loads, driving excitations, and structural flexibility during operation, resulting in dynamic response and vibration problems. Therefore, Finite Element Analysis (FEA) has been widely used in the study of mechanical arm structural performance, to evaluate structural stress, deformation, and dynamic stability [8]. Modal analysis can be used to extract the natural frequency and mode characteristics of a robotic arm, thereby identifying resonance risks; Harmonic response analysis can further evaluate the dynamic response characteristics of the structure under periodic excitation [9].

In contrast, although the research on path planning for domestic robotic arms started relatively late, it has developed rapidly in recent years. Related research mainly focuses on methods such as artificial potential field method, particle swarm optimization algorithm, fast random tree, and genetic algorithm [10]. In response to the problems of local optima and path oscillations in traditional path planning algorithms, domestic scholars have proposed various improvement strategies to enhance the path planning performance of robotic arms in complex environments. For SCARA robotic arms, due to their simple structure, high planar motion efficiency, and suitability for industrial assembly scenarios, research mainly focuses on planar trajectory planning and static obstacle avoidance analysis.

In the field of mechanical arm structural dynamics research, China mainly focuses on finite element modeling, modal analysis, harmonic response analysis, and rigid flexible coupling dynamics simulation [11]. With the widespread application of MATLAB and ANSYS simulation platforms, numerical simulation based performance analysis methods for robotic arms have gradually become a research hotspot.

However, existing research still has certain shortcomings. On the one hand, most path planning research mainly focuses on whether the robotic arm can complete obstacle avoidance tasks, and there is insufficient comprehensive evaluation of trajectory smoothness, structural dynamic response, and motion stability; On the other hand, research on the structural dynamics of robotic arms tends to focus on analyzing the vibration characteristics of the body, with less emphasis on combining path planning results with dynamic performance evaluation. The existing research has not yet formed an integrated analysis system for path planning and structural dynamic performance, which is difficult to support the engineering application of high-speed and high-precision SCARA.

In response to the above issues, this article proposes a comprehensive evaluation method of motion performance combining path planning and finite element analysis for four degree of freedom SCARA, and completes three tasks: structural analysis, obstacle avoidance planning, and integrated verification.

Firstly, a four degree of freedom SCARA robotic arm finite element model is established based on the ANSYS Workbench platform, and the stress distribution and structural deformation of the robotic arm under working load are studied through static analysis. Then, modal analysis is used to extract the natural frequencies and modal characteristics of the robotic arm and evaluate its dynamic stability. Finally, harmonic response analysis is performed to investigate the dynamic response characteristics of the robotic arm under periodic excitation.

Secondly, based on the MATLAB platform, establish a kinematic model and path planning simulation environment for the robotic arm, construct a static obstacle scene, achieve path planning and obstacle avoidance motion simulation for the robotic arm, and verify the feasibility and motion continuity of the path planning scheme.

Finally, based on the results of path planning and numerical simulation, a comprehensive evaluation of the motion performance of the robotic arm is conducted, providing theoretical reference for path planning and structural optimization design of the robotic arm.

2. Numerical Simulation Analysis of Mechanical Arm Structural Performance Based on ANSYS

2.1 Establishment of Finite Element Model

In the actual operation process, the robotic arm not only needs to complete trajectory tracking and obstacle avoidance tasks, but also needs to bear the effects of its own gravity, joint driving force, and end effector load. Therefore, its structural strength, stiffness, and dynamic stability will directly affect the movement performance and control accuracy of the robotic arm. In order to verify the rationality of the structural design of the four degree of freedom SCARA robotic arm and provide a reliable structural foundation for subsequent path planning algorithm research, this paper uses the ANSYS Workbench platform to perform finite element numerical simulation analysis on the robotic arm.

The research object of this article is a four degree of freedom SCARA robotic arm, which is mainly composed of a fixed base, a first rotary joint, a second rotary link, a vertical motion mechanism, and an end effector. Due to the typical cantilever structure of SCARA robotic arm, it is prone to structural deformation and vibration under high-speed motion and periodic excitation. Therefore, it is necessary to evaluate its structural performance.

During the finite element modeling process, the three-dimensional solid model of the robotic arm is imported into the ANSYS Workbench platform and the geometric model is appropriately simplified to improve computational efficiency. The simplified content mainly includes small structural features that have less impact on the overall force, such as threads, chamfers, and local decorative details. The material parameters adopt a linear elastic material model to meet the requirements of structural statics and dynamics analysis.

In terms of boundary conditions, the base of the robotic arm is set as a fixed constraint to simulate the actual installation of the robotic arm on the work platform; external loads are simultaneously applied at the end-effector position to simulate the force state of the robotic arm during grasping or handling tasks. On this basis, static analysis, modal analysis, and harmonic response analysis are carried out separately to comprehensively evaluate the structural performance of the robotic arm. The established finite element model is shown in Figure 1.

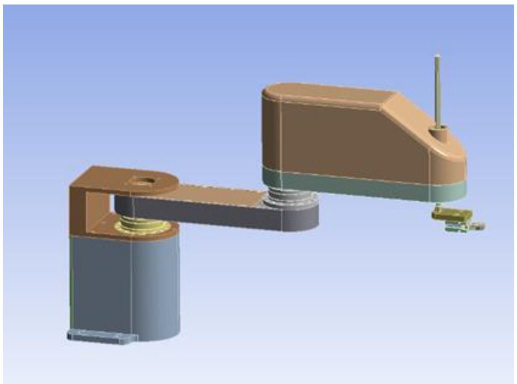


Figure1 SCARA robotic arm finite element model

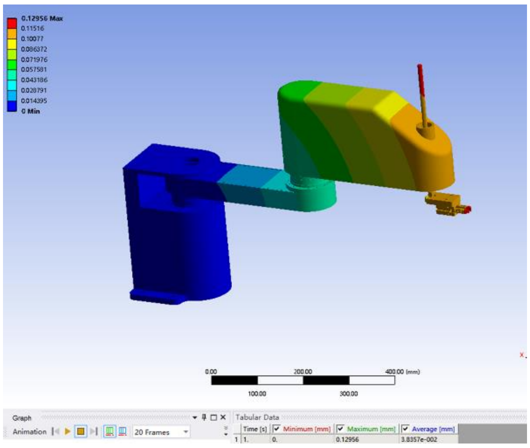
2.2 Static Analysis

In order to evaluate the structural strength and stiffness performance of the robotic arm under working loads, this paper uses the ANSYS Static Structural module to perform static analysis on the four degree of freedom SCARA robotic arm. Static analysis can reflect the stress distribution and deformation of the robotic arm under static working conditions, providing a basis for verifying the rationality of structural design.

During the analysis process, the base of the robotic arm is set as a fixed constraint and a working load is applied at the end effector position to simulate the force conditions when the robotic arm actually performs grasping tasks. As shown in Figure 2, the simulation results show that the maximum equivalent Von Mises stress of the manipulator reaches 216 MPa, which is lower than the allowable stress of the material and meets the strength requirements. The maximum equivalent stress is mainly concentrated in the joint connection areas of the robotic arm and near the end effector. This is because these regions transmit the main loads, while geometric structural changes lead to more pronounced local stress concentration.

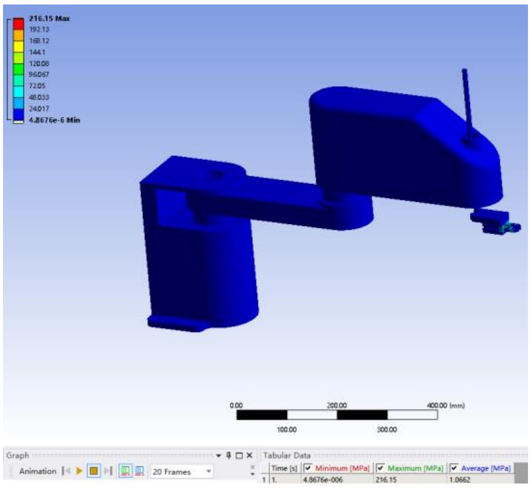
As shown in Figure 3, the maximum total deformation of the manipulator is 0.13 mm, with a small amount of deformation and stiffness that meets the requirements for positioning accuracy. In the end-effector region of the robotic arm, this is the normal response characteristic of a typical cantilever structure under external loads, indicating that the structural flexibility is mainly concentrated at the free end.

Overall, the deformation of the robotic arm is relatively small and the stress distribution is reasonable, indicating that the designed structure has good strength and stiffness, which can meet the requirements for structural stability in the path planning and motion control process of the robotic arm.



	Time [s]	☑ Minimum [mm]	☑ Maximum [mm]	☑ Average [mm]
1	1.	0.	0.12956	3.8357e-002

Figure 2 Static equivalent stress distribution diagram of robotic arm



	Time [s]	☑ Minimum [MPa]	☑ Maximum [MPa]	☑ Average [MPa]
1	1.	4.8676e-006	216.15	1.0662

Figure 3 Cloud map of total static deformation distribution of robotic arm

The analysis results indicate that the first-order frequency is 54.04 Hz, and the vibration mode is end plane bending vibration; Higher order is locally coupled bending torsion vibration, with the maximum vibration displacement concentrated in the free end region of the robotic arm; As the modal order increases, the vibration mode gradually exhibits local bending vibration and torsional coupling vibration.

Due to the fact that the actual working excitation frequency of the robotic arm is usually much lower than the first natural frequency, the working excitation frequency of the robotic arm under normal working conditions is much lower than the first natural frequency, and there is no resonance risk, indicating that the structure has good dynamic stability.

2.3 Modal Analysis

The robotic arm may experience vibrations during operation due to factors such as motor drive, inertial loads, and external periodic excitations. When the excitation frequency approaches the natural frequency of the structure, it is easy to cause resonance phenomenon, which affects the motion accuracy and structural life of the robotic arm. Therefore, this article uses the ANSYS Modal Analysis module to conduct modal analysis on the robotic arm to study its inherent vibration characteristics.

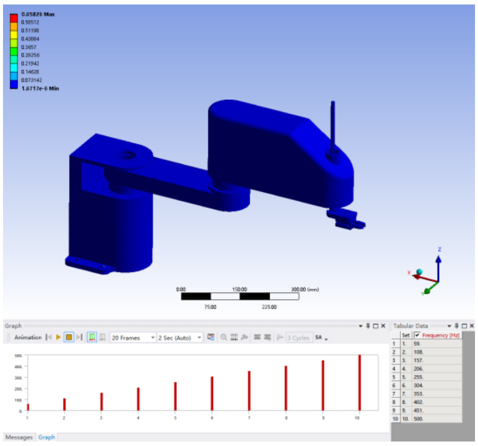
By extracting the first six modes of the robotic arm, the corresponding natural frequencies are obtained as shown in Table 1:

Table 1 Natural Frequency and Modal Characteristics Results of A Four Degree of Freedom SCARA Robotic Arm

Modal Order	Natural Frequency (Hz)
First-order	54.04
Second-order	89.45
Third-order	107.44
Fourth-order	109.85
Fifth-order	244.83
Sixth-order	281.94

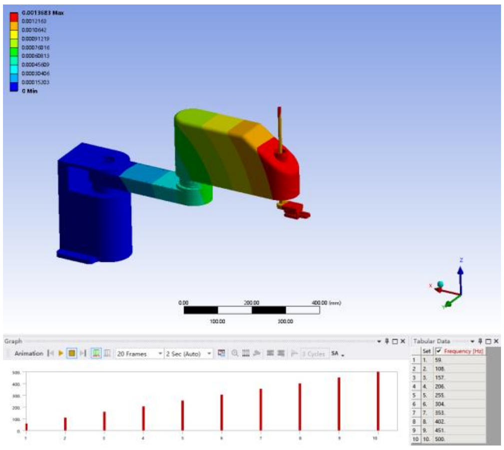
2.4 Harmonic Response Analysis

To further evaluate the dynamic response characteristics of the robotic arm under cyclic excitation loads, this paper uses the ANSYS Harmonic Response module to analyze the harmonic response of the robotic arm.



	Set	☑ Frequency [Hz]
1	1.	59.
2	2.	108.
3	3.	157.
4	4.	206.
5	5.	255.
6	6.	304.
7	7.	353.
8	8.	402.
9	9.	451.
10	10.	500.

Figure 4 Harmonic response equivalent stress distribution diagram



	Set	☑ Frequency [Hz]
1	1.	59.
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5	5.	255.
6	6.	304.
7	7.	353.
8	8.	402.
9	9.	451.
10	10.	500.

Figure 5 Harmonic response total deformation distribution diagram

During the analysis process, a harmonic excitation load is applied to the robotic arm within a certain frequency range to simulate the motor cycle driving and mechanical cycle disturbance conditions. As illustrated in Figures 4 and 5, the harmonic response results reveal that the maximum equivalent stress of the manipulator is only 0.658 MPa within the set excitation frequency range, and the maximum total deformation is 0.00137 mm. The dynamic stress and deformation are extremely small, there is no resonance amplification, and the anti vibration performance and dynamic stiffness are excellent.

3. Design and MATLAB Simulation of Path Planning Algorithm for Robotic Arm

3.1 Establishment of Kinematic Model for Robotic Arm

The implementation of robotic arm path planning relies on the establishment of an accurate kinematic model to describe the mapping relationship between the joint variables of the robotic arm and the spatial position of the end effector. The research object of this article is a four degree of freedom SCARA robotic arm, which is mainly composed of two planar rotation joints, one vertical movement joint, and an end effector. Due to its simple structure, high motion efficiency, and relatively clear modeling of planar path planning problems, SCARA robotic arms are widely used in industrial assembly and handling scenarios.

In order to convert the path planning results into actual motion control of the robotic arm, it is necessary to establish a kinematic model of the robotic arm. This article uses geometric methods to establish the planar kinematic relationship of SCARA robotic arm and performs numerical solutions based on MATLAB platform.

Let the lengths of the first and second connecting rods of the robotic arm be:

$$L_1 = 0.3m \quad L_2 = 0.25m \tag{1}$$

The position of the end effector of the robotic arm is: (x, y)

The forward kinematics expression is:

$$x = L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) y = \\ L_1 \sin \theta_1 + L_2 \sin (\theta_1 + \theta_2) \tag{2}$$

In the process of path planning, it is necessary to reverse calculate the joint variables of the robotic arm based on the end target position, so a further inverse kinematics model is established:

$$D = \frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2} \tag{3}$$

Second joint angle:

$$\theta_2 = \arctan (\frac{\sqrt{1 - D^2}}{D}) \tag{4}$$

First joint angle:

$$\theta_1 = \arctan \left(\frac{y}{x}\right) \\ -\arctan (\frac{L_2 \sin \theta_2}{L_1 + L_2 \cos \theta_2}) \tag{5}$$

Through the above model, the conversion of path points to joint motion variables of the robotic arm is achieved, providing a theoretical basis for subsequent path planning and simulation verification.

3.2 Modeling of Static Obstacle Environment

To verify the obstacle avoidance ability of the robotic arm in complex environments, this paper constructs a typical static obstacle environment for path planning research. Considering that industrial robotic arms often face the problem of fixed obstacle interference during actual operation, a two-dimensional static obstacle avoidance scene is constructed using double circular obstacles.

The center positions of obstacles are defined as: O_1 (x_1, y_1) O_2 (x_2, y_2)

The obstacle radius is set to R=0.05m

To ensure the safety of the robotic arm movement, a safety distance constraint is introduced: H=0.015m

The effective safe obstacle avoidance area is: R+H

To ensure the safe passage of the robotic arm through the obstacle area, the effective channel width between the two obstacles must meet the following requirement: gap>2H

As shown in Figure 6, this modeling method can effectively simulate the path planning problem of industrial robotic arms in fixed obstacle environments.

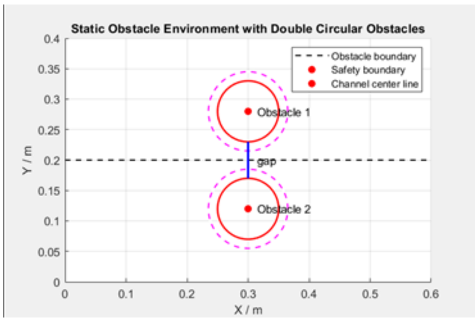

Figure 6 Schematic diagram of static double circle obstacle environment modeling

3.3 Design of Obstacle Avoidance Path Planning Algorithm

In a static obstacle environment, the goal of robotic arm path planning is to ensure obstacle avoidance safety while smoothly moving the end effector from the starting position to the target position. This article adopts a smooth obstacle avoidance path planning method based on PCHIP segmented cubic interpolation. Firstly, a feasible set of path points is established based on the spatial distribution of obstacles, and discrete path nodes are generated under the constraint of obstacle safety: P_i (x_i, y_i). Then, continuous trajectory interpolation is performed on the path nodes to construct a smooth trajectory for the end effector of the robotic arm: P (t)=f (P_i)

In order to improve trajectory continuity and motion smoothness, this paper uses the PCHIP (Piecewise Cubic Hermite Interpolating Polynomial) interpolation method in MATLAB for path optimization. Compared to simple linear interpolation, this method can effectively avoid the problem of sudden velocity changes at path turning points and improve the stability of robotic arm motion.

During the planning process, path generation must meet the following conditions:

(1) The end of the robotic arm can avoid obstacles in a safe area;

(2) The trajectory is continuous and smooth;

(3) There are no unreachable positions during the movement of the robotic arm;

(4) Satisfy the conditions for solving inverse kinematics.

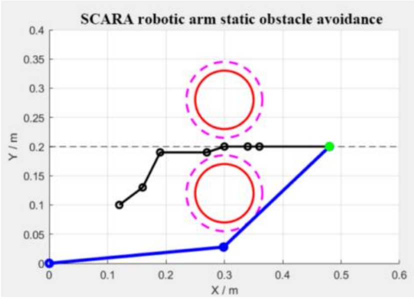

Figure 7 Result diagram of obstacle avoidance path planning for robotic arm

As shown in Figure 7, the static obstacle avoidance trajectory of the manipulator generated by the above method realizes the obstacle-free path planning task.

3.4 MATLAB Simulation Verification

To verify the effectiveness of path planning algorithms, this paper establishes a dynamic simulation model of a robotic arm based on the MATLAB platform. Based on the path planning results, the trajectory points are solved point by point using inverse kinematics, and the robot arm posture is updated by combining forward kinematics to achieve visualization of the robot arm motion process. The simulation results show that the robotic arm can complete continuous motion from the starting position to the target position along the planned trajectory, and successfully pass through the narrow area between two obstacles without collision during the entire motion process, indicating that safe obstacle avoidance and smooth trajectory tracking can be achieved, and joint motion is continuous without impact.

Meanwhile, due to the use of smooth trajectory generation method, the joint motion of the robotic arm is continuous and stable, avoiding the drastic attitude changes caused by path mutations, and verifying the feasibility and effectiveness of the path planning algorithm.

4. Conclusion

This article takes the four degree of freedom SCARA robotic arm as the research object, combines finite element structural performance analysis with path planning algorithm, and systematically carries out static, modal, harmonic response simulation, obstacle avoidance trajectory planning and motion verification research, forming a comprehensive evaluation method for the motion performance of robotic arms for high-speed and high-precision operations. The finite element analysis results show that the designed robotic arm has a reasonable stress distribution and small end deformation under typical working loads, and the structural strength and stiffness meet the requirements of engineering operations; The first-order natural frequency is far away from the conventional working excitation frequency, and there is no obvious resonance amplification phenomenon under periodic excitation. The overall system has excellent dynamic stability and anti vibration performance. A kinematic model based on MATLAB and PCHIP interpolation smoothing planning method can generate continuous and collision free safe trajectories in static obstacle environments. Motion simulation has verified that this method can achieve stable obstacle avoidance and smooth tracking, effectively avoiding joint motion impact and trajectory changes. Research has shown that coupling path planning with structural dynamics analysis can comprehensively evaluate the actual motion performance of robotic arms, overcome the limitations of single direction research, and provide theoretical support and technical references for trajectory optimization, structural improvement, and engineering applications of SCARA robotic arms in industrial scenarios such as electronic assembly and automatic handling.

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