Static and modal analysis of industrial robots

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Abstract: As an important automation equipment in contemporary manufacturing industry, 5-axis industrial robot is an important part of automated production. It improves the quality of work and production efficiency, reduces the workload of workers and lowers production costs. The development of industrial robots has a profound impact on China's goal of being among the world's manufacturing powerhouses in the first half of the 21st century. This paper presents a finite element analysis of the overall system of a five-axis intelligent robot for industrial use. The main focus is on optimizing the mechanical structure of the five-axis intelligent robot for industrial use, and the external structure of the key support components of the robot is simplified to create the model. Hazardous stress states were selected for the system analysis, a static analysis was implemented for each component to obtain the displacement and stresses corresponding to them, the maximum deformation of the key parts of the robot was obtained, and finally its stiffness was evaluated. Then the modal analysis is performed on this robot model, and the modal vibration clouds of the first 6 orders are selected to study the vibration patterns to obtain the corresponding frequencies, which provides data support for the robot to avoid working at resonant frequencies and provides a theoretical basis for improving its overall structure.

1. Introduction

Industrial robots are important equipment for production and manufacturing in the world and are widely used in various countries in industries such as train manufacturing, automobile processing, aircraft maintenance, motorcycle design, engineering equipment development, electronic information technology, mass production of civilian appliances, and hazardous chemical production instead of human beings, mainly for assembly, handling, processing, welding, painting, palletizing and other operations[1,2]. The industrial, machinery manufacturing industry has been the main battleground for robots since the first robot was born. The development of robotics in various countries has facilitated the process of industrial production, machinery manufacturing. To some extent, the rapid development of robotics is also promoting employment for all. Industrial robots are defined as multi-degree-of-freedom machines oriented to the mechanical industry and other related fields, which replace humans in the actual process of production and can automatically control and autonomously perform specific monotonous or frequent long-time operations. Special-purpose robots in industry are generally composed of three components and six related subsystems. The three components in the organization refer to mechanical equipment, control equipment, and sensing equipment[3,4]. Then the six related subsystems in the organization include mechanical architecture, mechanical dynamics, automatic manipulation, interface interaction, sensing feedback, human-machine interaction and other system components in this paper. A five-axis industrial robot is used as the object of study, and with the help of
ABAQUS software platform, the finite element method is used to divide the mesh to build a model of this five-axis robot and to conduct a systematic study of its static analysis and modal analysis. The deficiencies of the current research in industrial robots are analyzed and a theoretical basis is provided for the subsequent research.

2. Simulation analysis
Before dividing the mesh, the drive mechanism etc. inside the original five-axis industrial robot model is simplified, as shown in Fig. 1.

![Fig. 1 Five-axis industrial robot](image)

When meshing this five-axis industrial robot, the specific parameters are set in Table 1 below. Since this model has many rounded corners and chamfers, it needs to be finely meshed. The cell type is C3D4, the total number of cells: 317994; the total number of nodes: 88651.

| material | modulus of elasticity | Poisson's ratio | density       |
|----------|-----------------------|-----------------|---------------|
| Q235     | 210.5 GPa             | 0.3             | 7850 kg · m⁻³ |

3. Hydrostatic analysis
In order to obtain more accurate calculation results, the five-axis industrial robot was loaded in three different directions: x, y, and z. The analysis results are shown in Figures 2 to 4, and the data are listed in Table 2.

![Fig. 2 Static analysis of 5-axis industrial robot x-direction – displacement](image)
Fig. 3 Five-axis industrial robot static analysis y-direction – displacement

Fig. 4 Static analysis of 5-axis industrial robot z-direction-displacement

Table 2 Simulation analysis results

| Load Condition          | Maximum Stress | Maximum Displacement |
|-------------------------|----------------|----------------------|
| 1000N in x-axis direction | 15.3 MPa       | 0.18 mm              |
| 500N in y-axis direction | 12.5 MPa       | 0.44 mm              |
| 2000N in z-axis direction | 32.1 MPa       | 0.45 mm              |

The analysis results showed that the robot end-effector produced a maximum deformation of 0.45 mm under a maximum load of 2000 N, which satisfied the requirement of deformation less than 0.5 mm. The maximum stress is 32.1 MPa, which is also much less than the yield strength of Q235, and the mechanism can operate normally.

4. Modal simulation analysis

The vibration characteristics of the five-axis industrial robot are analyzed by looking at the order frequencies of the robot and observing its main vibration patterns. From the basic theory of modal analysis\(^5\), it can be understood that the five-axis industrial robot is most effective when it is subjected to low order frequency response, so the first 20 orders of its modal analysis is simulated, and the first 6 orders of modal vibration patterns at low order frequencies are taken to focus on the analysis.
The above 20th order intrinsic frequencies are shown in Table 3. From the first 20 steps of the modal vibration diagram, the maximum deformation that would occur at the first 12 steps of frequency all occur at the end-effector, with the maximum deformation at the 1st order intrinsic frequency of 3.08mm, the 2nd order of 3.83mm, the 3rd order of 3.11mm, the 4th order of 9.77mm, the 5th order of 7.42mm, the 6th order of 4.97mm, the 7th order of 3.79mm, the 8th order is 4.36mm, 9th order is 7.19mm, 10th...
order is 8.39mm, 11th order is 5.97mm, 12th order is 9.72mm, and the mode vibration pattern at the inherent frequencies of 13th to 20th order, the maximum deformation is transferred to the rotating table and the maximum deformation is 9.30mm.

| order of precedence | Inherent frequency |
|---------------------|-------------------|
| 1                   | 17.8Hz            |
| 2                   | 38.7Hz            |
| 3                   | 42.5Hz            |
| 4                   | 84.2Hz            |
| 5                   | 96.3Hz            |
| 6                   | 126.5 Hz          |
| 7                   | 145.6 Hz          |
| 8                   | 157.1Hz           |
| 9                   | 183.6Hz           |
| 10                  | 240.9Hz           |
| 11                  | 269.5 Hz          |
| 12                  | 279.5 Hz          |
| 13                  | 319.8Hz           |
| 14                  | 401.8Hz           |
| 15                  | 439.1Hz           |
| 16                  | 469.4Hz           |
| 17                  | 518.1Hz           |
| 18                  | 529.3Hz           |
| 19                  | 586.6Hz           |
| 20                  | 628.4Hz           |

Based on the above simulation analysis results, and because the frequency in the 10Hz ~ 130Hz will resonate with other equipment. In order to meet the needs of engineering work, this five-axis industrial robot should improve the design to avoid the range of resonance frequency occurrence.

5. Conclusion
This paper analyzes the static mechanics and modal simulation of the five-axis industrial robot based on the finite element software ABAQUS, and finds the location of the maximum deformation through the static analysis of the key parts; through the modal simulation of the five-axis industrial robot, the first twenty orders of inherent frequency are solved, and the first six orders of inherent frequency are found to be within the range of the vibration frequency of the mechanism operation. The above analysis provides an effective basis for the improvement of the five-axis industrial robot.

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