Structural Dynamics Simulation Analysis of Industrial Robot Arm Based on Kane Method

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Abstract. When the traditional methods are used to analyze the dynamics of the robot arm structure, the stability of the arm structure is not good and the simulation effect of the operation process is not good. For this reason, Kane method is introduced in this paper to carry out dynamic simulation analysis of industrial robot arm structure. The operating process of the industrial robot arm structure was simulated by Kane method, and the angular acceleration of the robot’s main arm, forearm and push rod was solved in each cycle. The Jacobian matrix of the 5 degree of freedom manipulator joint is established, the singular configuration of each joint is calculated, and multiple joint variable combinations are generated by random number. The forward motion equation of the robot endpoint set was solved to obtain the endpoint set of the robot. The Lagrangian method was used to model the robot with Kane 3D simulation software to simulate and analyze the dynamic process of the driving torque required to grasp the mass workpiece at the three joints. The joint motion model of robot is established on ADAMS simulation software, and the torque curve of the rotating joint of industrial robot arm structure is obtained. MATLAB simulation software is used for simulation. The results show that the integrated design method of manipulator and machine tool is correct, which provides a comprehensive data basis for the selection of servo motor.

1. Introduction

Industrial robot arm is a new high-tech interdisciplinary, which is the synthesis and intersection of multi-disciplinary knowledge. The kinematics and dynamics of manipulators is one of the important contents of robotics. As an important automation equipment in modern manufacturing industry, industrial machine is widely used in industry, and the design method of industrial robot arm structure is developed\textsuperscript{(1,2)}. The dynamic theory and application of manipulator is an important subject in the research and design of manipulator.

When the traditional method is used to design the structure of the robot arm, the control effect on the stability of the robot arm is not good, and the control accuracy is poor. This paper presents a dynamic simulation analysis method of industrial robot arm structure based on Kane method. In this paper, the working process of the arm structure of industrial robot is simulated, and the angular acceleration of the main arm, forearm and push rod of the robot in each cycle is solved. The combination of multiple joint variables is generated by random number, and the robot endpoint set is obtained by solving the forward motion equation of the robot endpoint set. Based on Kane three-dimensional simulation software, the dynamic process of the driving torque needed to grasp the
large-scale workpiece at three joints is analyzed. The method in this paper can effectively improve the accuracy of the robot grasping and the stability of the structure.

2. Dynamic simulation analysis of industrial robot arm structure

2.1. Structure analysis of industrial robot arm

In order to meet the needs of engineering application, a modular light load handling robot with high flexibility and low cost is designed. Its loading weight can reach 3 kg, and it can be well used in repeated routine handling operations\(^3\). The robot consists of six joints, six of which are rotating joints. The size of the first three sections a, l and u are the same, the motor power is 400 W, the deceleration ratio is 120 knots, the motor power is 100 W, and the reduction ratio is 100. Its characteristics are: the joint structure is simple, light weight, mainly composed of joint shell, engine and deceleration mechanism; there is no complex structure in the inner side, and the joint diameter is only 8 times larger than that of the deceleration mechanism\(^4\). The external ur robot, only l, u and u, R joints are connected through the arm tube, and other joints are directly connected; the rear three joints of the robot are perpendicular to each other to ensure the flexible movement of the robot. Based on the overall design, the 3D model of the robot is drawn with solid works 3D design software, as shown in the figure.

![Three dimensional structure display of robot arm.](image)

When the manipulator runs smoothly, the multi joint synovial controller keeps connected all the time, scans and sorts out the documents that can not be digested in time, and allocates them to each level of operation structure through the input channel, so as to play the physical executive function of connecting the preceding with the following\(^5\).

The multi degree of freedom robot is regarded as a series of connecting rods, which are mainly composed of manipulator, rotator, moving parts, transmission parts, end effector, etc. To describe the relationship between two links by Kane principle, a coordinate system must be specified on each link of the manipulator. In this paper, the relationship between the manipulator and the fixed coordinate system is described by using 4x4 homogeneous transformation\(^6\). The homogeneous transformation matrix between the end coordinate system and the reference coordinate system of the manipulator is derived, and its motion equation is established. D-H matrix is used to represent the coordinate transformation matrix of the end bar relative to the fixed coordinate system.

\[
^{R}_E T_E = A_1 A_2 A_3 A_4 A_5^T \Rightarrow \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
\]

The robot has six rotating joints, and the center of each joint is fixed in six positions. The z-axis with the off axis as the coordinate system is vertical or parallel in each coordinate system. Based on the structural characteristics of modular light load handling robot, the link type coordinate system is established and optimized by D-H method. For the complex configuration of light load industrial robot, Lagrange analysis method is used to analyze its dynamics.
2.2. Topology optimization design of industrial robot

According to the lightweight characteristics of the robot, a topology optimization model is proposed. The model can meet the requirements of structural strength and natural frequency, and achieve the goal of lightweight\(^7\). Set the angle variable of the robot's six joints:

$$\theta = [\theta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5 \ \theta_6]$$

(2)

The driving torque of the joint is variable:

$$T = [T_1 \ T_2 \ T_3 \ T_4 \ T_5 \ T_6]$$

(3)

The kinetic energy of the manipulator is:

$$K_i = \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} \text{Trace} \left( U_j U_k^T \right) \dot{\theta}_j \dot{\theta}_k + \frac{1}{2} \sum_{i=1}^{n} I_i \dot{\theta}_i$$

(4)

Where \( U_j \), \( U_k^T \) are the transformation matrix, \( J_i \), \( \dot{\theta}_i \) is pseudo inertia matrix and driving inertia. Since the potential energy of the linkage is equal to the sum of the potential energies of all the linkages, it can be expressed as follows:

$$P = \sum_{i=1}^{n} p_i = \sum_{i=1}^{n} K_i \left[ -m_g \dot{r}_i \right]$$

(5)

In the above algorithm, \( g_1 \) is a \( 1 \times 4 \) matrix, which is the projection of gravity acceleration of connecting rod in \( x, y, z \) direction, coordinate transformation between \( \tau_i \) coordinate system and reference coordinate system, that is, the position of connecting rod centroid in \( r \) coordinate system.

The following is the Lagrange equation:

$$L = K - P = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \text{Trace} \left( U_j U_k^T \right) \dot{\theta}_j \dot{\theta}_k + \frac{1}{2} \sum_{i=1}^{n} I_i \dot{\theta}_i^2 - \sum_{i=1}^{n} \left[ -m_g \dot{r}_i (T_i) \right]$$

(6)

The driving force equation of each joint of the manipulator is as follows:

$$T_i = \frac{\partial \left( \frac{\partial L}{\partial \theta} \right)}{\partial \theta} - \frac{\partial L}{\partial \theta}$$

(7)

The derivative terms obtained by decoupling are as follows:

$$T_i = \frac{\partial L}{\partial q_p} \dot{q}_i + \frac{\partial L}{\partial \theta} - H(q) \ddot{q}_i + C(q, \dot{q}) \dot{q}_i + G(q)$$

(8)

$$= \frac{\partial L}{\partial q_p} \sum_{j=1}^{n} D_j \ddot{q}_j + I_i \dot{\theta}_i + \sum_{j=1}^{n} \frac{\partial L}{\partial q_p} \sum_{k=1}^{n} D_j \dot{q}_j \dot{q}_k + D_i$$

Where: \( \sum_{j=1}^{n} D_j \ddot{q}_j \) represents the influence of inertial force caused by generalized angular acceleration on the dynamic system; \( I_i \) is a term of inertia produced for a driving device such as a motor; \( \sum_{j=1}^{n} \sum_{k=1}^{n} \) \( q_j q_k \) are Coriolis force and centripetal force respectively; \( D_i \) is the gravity term that affects the joint torque. The joint space vector \( q \) is used as a random point to act on the joint angle of the robot

$$q_i = q_{\text{min}} + (q_{\text{max}} - q_{\text{min}}) \text{rand}(j)$$

(9)

In the specified time, complete the preset of each joint, speed and acceleration. When the position
of a point in the workspace is known, through the trajectory of the joint space, the motion controller calls the inverse kinematics equation to calculate the number of joints, and then controls the output of the driver to make the manipulator move to the predetermined position.

2.3. Dynamic structure optimization of robot arm

In order to reduce the difficulty of pre-processing and shorten the time of finite element simulation calculation, the simplified finite element model must be simulated, which can not only reflect the actual force situation of operators, but also be simple and easy to operate. The optimization steps of arm structure dynamic characteristics are further standardized as follows:

![Figure 2. Optimization steps of industrial robot arm structure dynamic characteristics.](image)

3. Analysis of experimental results

In order to verify the structural dynamics simulation effect of industrial robot arm based on Kane method, the simulation was completed in the laboratory control room with the help of Matlab's powerful calculation ability and good graphic processing ability. When the capacity of the control simulator is 1080 T, it can ensure that the existing literature can scan the joint state of the manipulator, and its parameter is 0.66. The test time of 60min is recorded respectively. After the control of the experimental group and the control group, the joint transmission performance of the manipulator has changed, and detailed test comparison is carried out.

| Experiment time/ (min) | Joint transmission capacity of manipulator/ (%) | change rule | Average transmission capacity level/ (%) |
|------------------------|-----------------------------------------------|-------------|----------------------------------------|
| 10                     | 90.61                                         | stable      |                                        |
| 15                     | 90.61                                         | rise        |                                        |
| 20                     | 93.42                                         | stable      |                                        |
| 25                     | 90.42                                         | rise        |                                        |
| 30                     | 91.42                                         | stable      |                                        |
| 35                     | 92.27                                         | stable      |                                        |
| 40                     | 92.27                                         | rise        |                                        |

Table 2. The transmission capacity of the control arm joints.

| Experiment time/ (min) | Joint transmission capacity of manipulator/ (%) | change rule | Average transmission capacity level/ (%) |
|------------------------|-----------------------------------------------|-------------|----------------------------------------|


In order to solve the problem of large peak interference in the process of output resonance response analysis of all transfer manipulator units, the point with larger amplitude is proposed as the field output requirement range of modal analysis, that is, the next node with the greatest impact of amplitude on the mechanical performance. Kane method is used to analyze the resonance response. The lower the resonance frequency is, the better the mechanical design of industrial robot arm structure is. Based on this, the single frequency end displacement response curve under horizontal resonance excitation is obtained. The specific detection results are shown in the figure below.

![Comparison test results.](image)

As shown in the figure, when the dynamic load frequency changes in the horizontal direction, the peak value of single frequency displacement response appears within 60Hz under the dynamic load of different frequencies. The results show that the frequency response of the structure is obviously smaller than that in the horizontal direction, mainly due to the vibration caused by the dynamic load in the horizontal direction. On the whole, the response of excitation frequency is a peak value. According to the modal analysis, the third natural frequency of the transfer robot is very close to its maximum displacement frequency response. The third natural frequency of the manipulator is easy to produce resonance. It can be seen from the vibration mode diagram that the third mode shape is mainly the bending vibration of beam and column end which is far away from the control position. From the symmetry, it can be seen that the manipulator moves with the movement of the sliding platform, and the bending vibration of the opposite end of the beam and the column also occurs at the other end. It is an important purpose to improve the dynamic performance of the transfer manipulator to improve its working stability, optimize its dynamic characteristics, improve its dynamic stiffness, and greatly reduce the vibration amplitude of the beam constrained by it.

4. Conclusion
According to the existing research foundation of the manipulator feed, combined with the application requirements of the manipulator, the structural dynamics simulation analysis of the industrial manipulator is carried out by using the karenka method, and a rotating manipulator is designed to realize the vertical two-stage lifting. The modal analysis and coordination response analysis of the whole structure of the robot are carried out by using Kane method, and the low order vibration mode
and frequency response curve of the mechanism are obtained. According to the characteristic that the natural frequency of the robot is the third order, the optimization measures of mechanical integral column installation are proposed. The rotating robot adopts the split frame structure, the vertical mobile robot adopts the inner and outer two arm nested structure, and the synchronous belt lifts the outer arm to achieve the two speed effect. It can effectively reduce the space height requirements of operators and increase the stability. The example analysis shows that the method proposed in this paper has good optimization effect.

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