The dynamic characteristic analysis on Cartesian coordinate robot

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Abstract. In this paper, the finite element analysis of the Cartesian coordinate robot and the modal analysis of the whole system of the robot are carried out. The axes of the robot will not resonate with the whole structure of the robot in the moving state. The motion of the first three workpieces is analyzed by using ADAMS motion simulation software. It is concluded that the robot motion state is stable, the speed changes smoothly, and the trajectory runs reasonably.

1. Introduction
In the process of movement, the Cartesian coordinate carrying robot bears a large load and has a fast speed. In the process of reciprocating motion, there will be some vibration deviation or structural deformation. In this state, the dynamic characteristics of the robot play an important role in the reliability of the whole system. If it is not analyzed, it may affect the normal work of the robot and cause uncertain factors to the path control planning of the robot, so it is very necessary to analyze the dynamic characteristics of the robot.

2. Basic theory of modal analysis
Modes are the natural dynamic characteristics of an object. Each mode has a specific natural frequency, damping ratio and mode shape [1]. These modal parameters can be obtained by calculation or test analysis[2]. Such a process of calculation or test analysis is called modal analysis. The robot is assumed to be a linear elastic vibration system with n degrees of freedom, and its motion differential equation is as follows:

\[ [M]\ddot{X} + [C]\dot{X} + [K]X = \{F(t)\} \]  (1)

[M],[C],[K] are the mass, damping and stiffness matrices of the system respectively. \{X\}, \{\dot{X}\}, \{\ddot{X}\}, F are the displacement, velocity, acceleration response vector and excitation force vector of each point of the system.

If the initial state of the system is set to zero, then the Laplace transformation of equation (1) can be obtained:

\[ (S^2[M] + s[C] + [K])(X(S)) = [Z(S)][F(S)] \]  (2)

X(S) and F(S) are the Laplace transformation of displacement response and excitation force of each point of the system respectively. [Z(S)] is the system dynamic matrix, and its inverse matrix [H(S)] is the transfer function matrix.

From equation (2), it can be concluded that:

\[ \{X(S)\} = [Z(S)][F(S)] \]  (3)

With \( j_0 = S \), the relationship between the input and output of the system in the frequency domain
can be obtained by equation (3):
\[
\{X(W)\} = [H(w)]\{F(w)\}
\] (4)

\(H(w)\) is the frequency response function matrix.

If \(j\omega = S\), equation (2) becomes:
\[
(-w^2[M] + jw[c] + [k])\{X(w)\} = \{F(w)\}
\] (5)

Bring the following formula into (5):
\[
\{X(W)\} = [\psi]\{q\}
\] (6)

Equation (7) multiply \([\varphi]^T\) by left:
\[
(-w^2[M] + jw[c] + [k])\{q\} = [\varphi]^T\{F(w)\}
\] (7)

The undamped free vibration equation of equation (1) can be expressed as:
\[
[M]\{\ddot{X}\} + [k]\{X\} = 0
\] (9)

In modal analysis, the general structure is assumed to be linear \(X = [\varphi]e^{j\omega t}\), \(\varphi\) is the column vector of node displacement vibration amplitude, W is the natural frequency of vibration, available:
\[
[k] - w^2[M][\varphi] = 0
\] (10)

Through equation (10), Neigenvalues \(w_1^2, w_2^2, w_3^2...w_N^2\) and corresponding N eigenvectors can be obtained \([\varphi_1],[\varphi_2]...[\varphi_N]\). Where the square root of the eigenvalue \(w_i\) \((i = 1,2...n)\), it is the i-th natural frequency of the structure. The eigenvector \([\varphi_i]\) \((i = 1,2...n)\) is the first mode shape of the structure. All \([\varphi]\) constitute the natural mode matrix \([\varphi]\).

3. Structure simplification and grid division
In the finite element analysis of the robot as a whole, due to its large mass and structural load, the amount of calculation to solve the model will also increase, and the time consumed will be longer [3]. Therefore, appropriate structural simplification will not only have a small impact on the analysis results, but also shorten the calculation time. After the model is established, it is saved and imported into ANSYS Workbench, and the whole robot model is meshed by the same method of static analysis, as shown in Figure 1.

4. Overall modal analysis of robot
After the whole robot is meshed, the structure type of each part is defined. As the robot is fixed on the ground, the support is fixed and constrained; the axes move with each other, and the moving sliders of each axis are defined as friction free contact; the other contact surfaces are defined as sliding free contact[4]. Since the robot system consists of numerous frequencies, but the lower frequency has the greatest impact on the robot system, the first six modes of the robot are analyzed to obtain the first six natural frequencies of the robot shown in table 1 and the corresponding vibration modes of the sixth vibration frequencies in Figure 2.
Table 1. Robot first six frequencies and vibration modes

| Order | Frequency | Mode description                  |
|-------|-----------|-----------------------------------|
| 1     | 15        | Robot swings along X axis          |
| 2     | 22        | Robot swings along Y axis          |
| 3     | 30        | Robot twisting around central axis |
| 4     | 46        | Robot vibrates along Z axis        |
| 5     | 65        | Robot z-axis swings around X-axis  |
| 6     | 90        | Robot z-axis swings around y-axis  |

The first-order vibration of the robot is that the whole robot swings along the x-axis direction. The x-axis is the axis with the largest travel of the robot. The movement of the robot on the x-axis is realized by the motor driving the linear motion unit slider and then driving the z-axis.

The rotation speed of the belt pulley of the x-axis linear motion unit is 388 rpm, so the excitation frequency of the x-axis of the robot is 6.47 Hz, far less than the first-order natural frequency of the robot, 15 Hz, so it will not cause resonance. The second to sixth order natural frequencies of the robot are much higher than the excitation frequencies of the robot itself, so the dynamic performance of the robot design meets the requirements, and lays the foundation for harmonic response analysis.

(a) First order vibration mode
(b) Two order vibration mode
(c) Three order vibration mode
(d) Four order vibration mode
(e) Five order vibration mode
(f) Six order vibration mode

Figure 2. Vibration mode corresponding to sixth order frequency of robot.

5. Conclusion
The modal analysis of the whole robot system shows that the axes of the robot will not resonate with the whole structure of the robot in the moving state; the motion of the first three workpieces is analyzed by using ADAMS motion simulation software, and it is concluded that the robot motion state is stable, the speed changes smoothly, and the trajectory runs reasonably.

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