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Finite Element Modal Analysis of an Eight-axis Industrial Robot Painting System Applied to Boarding Bridge Painting

Abstract: An eight-axis industrial robot painting system (EIRPS) for painting the boarding bridge is presented. In order to understand the dynamic performance of this robot system, the finite element analysis software Workbench is used to make the modal simulation in this paper. Firstly, the overall mechanical structure of the EIRPS is described. And then, the finite element model is built and the modal analysis procedures are set out detailedly. In a configuration which conforms to the actual situation, the natural frequencies and corresponding vibration modes of the first six orders of the robot system are obtained. On the basis of the calculation results, relative weak parts of the robot system are shown and the optimum proposals are put forward. The analysis results indicate that the modal analysis of the mechanical structure of the EIRPS is reasonable.

Keywords: Finite element analysis; Modal analysis; Eight-axis; Modeling; Industrial robot; Painting System; Boarding bridge.

1 Introduction

Nowadays, movable terminal-to-aircraft structures such as boarding bridge finished with primer and topcoat could last over 10 years even while suffering extreme weather conditions and constant use. Jetway systems coat the interior of its passenger boarding bridges with a rust-inhibitive, water-reducible white primer. The exterior is finished with epoxy primer and a polyurethane topcoat. The combination provides adhesion and resistance to impact, abrasion and corrosion. Therefore, flexible painting robot system for large boarding bridges has become the hot topic of the current research [1].

At present in domestic, spray painting operation mainly relies on manpower to complete in most manufacturing factories, especially during the surface coating

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process of boarding bridge [2], as shown in Figure 1. The quality consistency of products obviously depends on the proficiency of the spray painters, while the respray ratio is high and the productivity is low. Moreover, the cost of labor is high and the environment of spray painting room is terrible, which is harmful to the workers' health [3]. Therefore, it is necessary for the enterprises to use automation equipment to replace manual operation.

Figure 1. The current painting process for the boarding bridge.

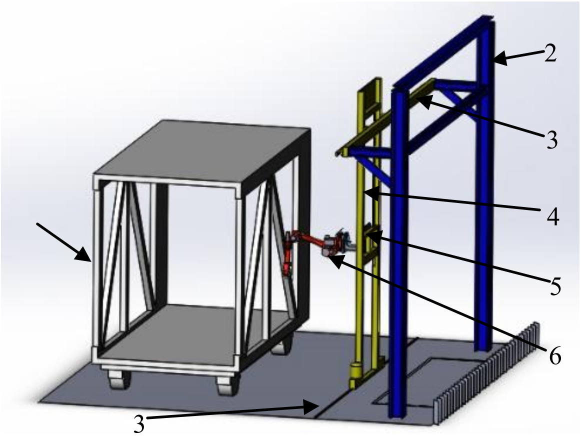
Vibration is an inevitable old problems for mechanical structures. Because the working stability, reliability and accuracy of the robot system could be directly influenced by the vibration characteristics. Moreover, it can cause the mechanism fatiguing or resonating, and even make the structure destroyed. Modal analysis is an effective method to demonstrate the dynamic performances of the mechanical structures [4,5], such as damping factors, natural frequencies and vibration modes and so on. Through the modal analysis, we can intuitively see the strength and weakness of the existing mechanical structures and the corresponding vibration modes. And it is helpful to improve the dynamic rigidity and vibration resistance of the structure at working state.

What the mostly used methods in modal analysis are the vibration experimental method and the finite element analysis method. Therefore, a lot of researchers focus on the hot spot of modal analysis. For example, T. Nagarajan [6] and his mates made a survey of the finite element methods applied to the dynamic analysis of the robot manipulators. J. Tlusty [7] and Q.K. Han [8] studied the modal parameters by using the dynamic structural identification task methods and vibration experimental method respectively. C. Yun [9] and X.P. Liu [10] researched the dynamic performance of the spot welding robots with experimental modal analysis method too. Evidently, experimental method helps to obtain the vibration parameters of the robots more accurately, but its cost of both time and expenditure are usually high. Luckily, the finite element modal analysis provides a convenient and feasible pathway to evaluate the structure performance and make the further optimization for the structure, especially during the structure design stage of the robot system [11-13].

This paper introduces a new kind of EIRPS for painting the boarding bridge. The optimized robot system can paint the boarding bridges efficiently on the basis of the conclusions of the finite element analysis in section III.

2 Structural DESCRIPTION of the EIRPS

This automatic painting robot system adopts the structure of a mobile lifting platform carrying a wall-mounted six-joint manipulator. The integral mechanical structure model of the robot system mainly includes Y-axis guide rails, Z-axis guide rails, lift, support plate, six-axis manipulator, as shown in Figure 2. The six-axis manipulator mainly includes body and external devices. Its body includes base, shoulder, large arm, elbow, small arm, wrist and flange which is used to installed the end-effector, as shown in Figure 3. These parts constitute six motion-coupled joints such as S, L, U, R, B, T axis. And the external devices mainly includes electric control cabinet, operation panel, centralized paint-feeding system, spraying gun and the fixture module of the spraying gun.

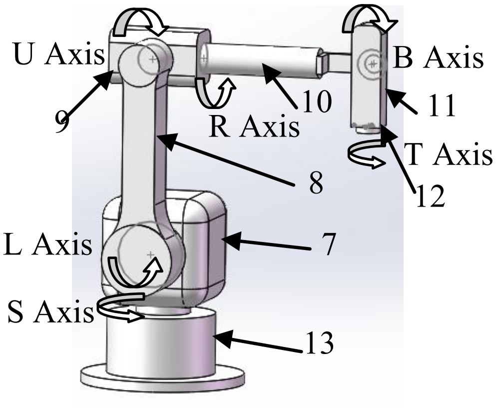


1-Boarding bridge
2-Stand
3-Y-axis guide rails
4-Z-axis guide rails
5-Lift
6-Six-axis manipulator

Figure 2. The integral structure model of the robot system.

As shown in Figure 2, the Y/Z two-external-axis linear coordinate motion system adopts the type of gantry layout and the six-axis manipulator is installed on the lifting platform. The boarding bridge is very large and its two sides are truss structure. The spray painting task includes not only the outside surface of the boarding bridge, but also the inside surface. So the six-axis manipulator should be flexible enough to stretch into the inside of the boarding bridge through the hole of the truss.

Additionally, the paint is inflammable and explosive goods, the painting location should prohibit fire and select explosion-proof electrical equipment. Such conditions require that the driving motors of the manipulator should not be exposed to the outside and manipulator's size should not be too large. Therefore, a manipulator of small and explosion-proof type is preferred and the two external translation axes are added to expand the workspace.



7-Shoulder
8-Large arm
9-Elbow
10-Small arm
11-Wrist
12-Flange
13-Base

Figure 3. The simplified model of manipulator.

3 Modal analysis of the eirPs

3.1 Theoretical basis of the modal analysis

Modal analysis is the study of the natural frequency and main modes of mechanical system. The natural frequency and vibration displacements are two important parameters on the dynamic performance of the mechanical structure, which are helpful for optimizing the structural system with eliminating noise and vibration. Both of them are only related to the rigidity characteristics and mass distribution of the structure, and have nothing to do with external factors. So modal analysis can be studied through the free vibration of the system. The motion equation of the typical undamped free vibration system can be represented as:

$$[M]\{\ddot{x}\}+[K]\{x\}=\{0\} \tag{1}$$

Where, $[M]$ is mass matrix; $[K]$ is stiffness matrix; $\{\ddot{x}\}$ is acceleration vector; $\{x\}$ is displacement vector. Then the general form of the solution of the above equation can be expressed as:

$$\{x\} = \{\mu\}\, sin(\omega t + \varphi) \tag{2}$$

Where, $\{\mu\}$ is real constant vector, ω is the frequency of simple harmonic motion, φ is an arbitrary constant. From (1) and (2), the characteristic equation of structural free vibration can be obtained:

$$([K] - \omega^2[M])\{\mu\} = \{0\} \tag{3}$$

It can be seen that (3) is a linear homogeneous algebraic equation, which is the problem of the classical characteristic value. The characteristic root of the frequency equation is ω_i^2 and ω_i is called the natural vibration circular frequency, $\omega_i/2\pi$ is the inherent frequency [3]. Put ω_i^2 into the characteristic equation (3), the eigenvector $\{\mu_i\}$ corresponding to the characteristic value can be solved. The eigenvector $\{\mu_i\}$ is known as modal vector, which embodies the vibration mode of the structure. These two parameters of the inherent frequency $\omega_i/2\pi$ and the modal vector $\{\mu_i\}$ are the specific nature of the structure itself, and they have nothing to do with the applied load, so they reflect the dynamic characteristic of structure.

3.2 Finite Element Modeling of the EIRPS

The whole system structure contains a lot of small features such as small screw holes, small convex platform, corners and fillets and so on. The existence of small features may lead to mesh generation too dense, even mesh failed. So the model should be properly simplified for improving the quality of mesh [4]. The finite element model of the simplified robot system and six-axis manipulator are respectively shown in Figure 4 and Figure 5.

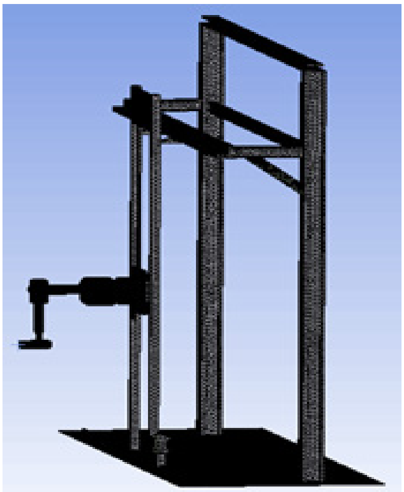


Figure 4. The FEM of the EIRPS.

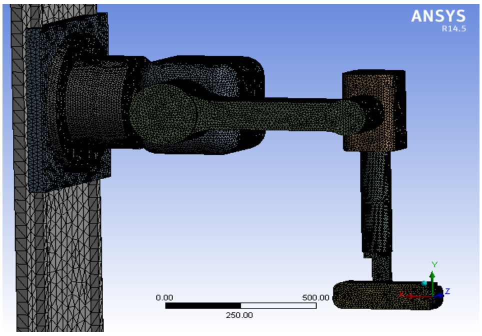


Figure 5. The FEM of the simplified six-axis manipulator.

We use ANSYS Workbench as the integrated simulation platform to make modal analysis of the EIRPS [5]. Then, the following demonstrates the detailed procedures for the modal analysis.

1) *The definition of material property of each part.* According to the operating condition, the materials of the main components such as the Y-axis guide rails, Z-axis guide rails, elevating platform, and foundation support adopt the structural steel while the six-axis manipulator adopts the cast aluminium.
2) *The application of the constraints.* In modal analysis, in order to simulate the actual installation condition of the robot system, the bottoms of the Y-axis guide rails and stand are fixed on ground.
3) *The settings of the connecting relation.* Binding contact processing method is used for the connected component interface of the spraying robot through fasteners. And the bottoms of the stand and ground rail are handled as fixed support.
4) *The meshing of the model.* Meshing is one of the most fatal steps in the modal analysis. Its quality will directly determine the precision of the result and the calculation time. In view of both the accuracy and the computer arithmetic ability, the tetrahedrons dominant meshing method is used to get the distribution of the mesh. Its total number of nodes is 1613135 and the total number of elements is 992729. The size of the element is 40mm. The execution part of the robot system can be simplified as 11 bodies and the element sizes are divided according to the different sizes of the parts, as shown in Table 1.

Table 1. The scope and element size of mesh

Object Name	**Body Sizing1**	**Body Sizing 2**	**Body Sizing 3**	**Body Sizing 4**	**Body Sizing 5**
Geometry	Stand	Y-axis guide rails, Z-axis guide rails	Lift Base	Shoulder elbow Large-arm	Small-arm Wrist Flange
Element Size (mm)	50	30	20	10	8

3.3 The results and analysis of the EIRPS modal simulation

In the practical engineering application, it is often just required to solve the first six orders natural frequencies and vibration modes of the robot system. Because in the general case, only the natural frequencies and vibration modes of the first few orders may cause structure to generate the risk of resonance.

Through calculating of the workstation, the inherent frequencies and corresponding vibration modes of the first six orders are obtained, as shown in Table 2.

Table 2. The total deformations and frequencies of the bodies

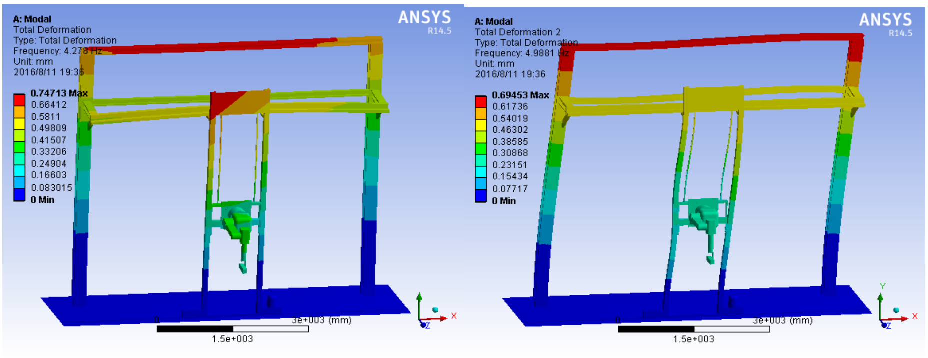
Mode	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**
Minimum *deformation*(mm*)*	0					
Maximum *deformation*(mm*)*	0.7471	0.6945	1.0469	1.188	1.4184	1.8653
Minimum occurs on	Guide rails					
Maximum occurs on	Stand	Stand	Stand	Large arm	Flange	Lift
Frequency(Hz)	4.278	4.9881	6.115	7.412	9.6998	13.342

As the color cloud pictures of the total deformations shown in Figure 6, the natural frequencies of the robot system are relatively low and their maximum deformations are gradually increasing by orders. The maximum deformations of the first three orders all occur on the top of stand. The maximum deformations of the latter three orders separately occur on the large arm, flange and lift. The Y-axis guide rails almost have no vibration, which indicates that the dynamic rigidity of these supporting parts is enough to cope with the low frequency vibration. The stiffness of the large arm, flange and lift should be reinforced to improve the dynamic rigidity and vibration resistance.

According to the data, the mechanical properties of the optimized system can be evaluated, resonance could be avoided and the structural stability could be ensured.

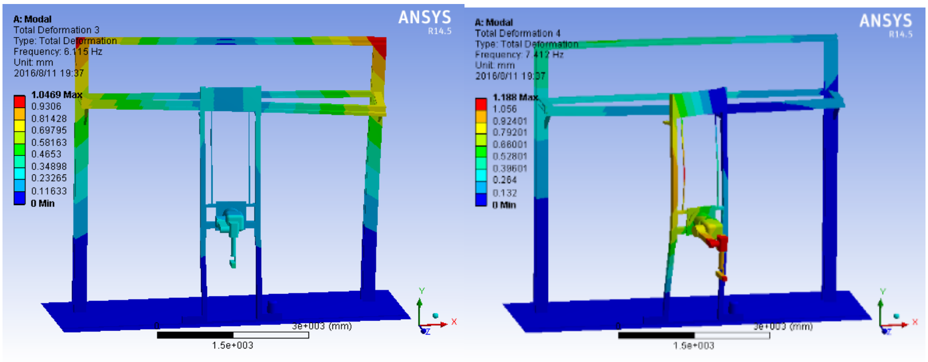
4 Conclusion

The mechanical structure of the eight-axis industrial robot painting system for boarding bridge is introduced in this paper. The system consists of a S/L/U/R/B/T six-joint manipulator, Y/Z two external translational axes, electric control cabinet, operation panel, centralized paint-feeding system, spraying gun and the fixture module of the spraying gun.



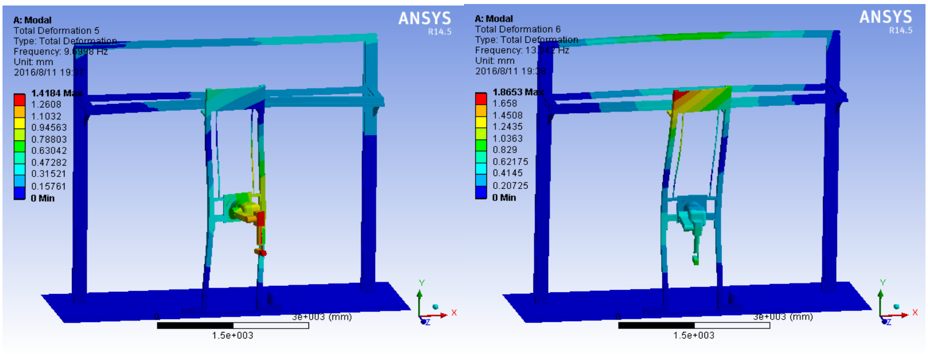
a. The first order vibration mode

b. The second order vibration mode



c. The third order vibration mode

d. The fourth order vibration mode



e. The fifth order vibration mode

f. The sixth order vibration mode

Figure 6. The vibration modes of the EIRPS.

The modal simulation analysis is demonstrated by finite element analysis software Workbench. The first six orders natural frequencies and the corresponding mode shapes of the robot are obtained. The conclusions drawn from simulation are as follows:

The natural frequencies of the robot system are relatively low and their maximum deformations are gradually increasing as order increasing. They should eliminate the negative effects brought by low order modes vibration at working state.

The stand is the most possible part to vibrate. It should use stronger and lighter material. Large arm and flange of the 6-joint manipulator and the lift also are the weak parts during vibration. Its stiffness should be increased for the better dynamic performance.

Because the stiffness of the joints will affect the accuracy of the modal analysis result of the manipulator, the joints should be focused on when simplifying the model. The stronger and stiffer the robot model is, the preciser analysis result will be.

In the future work, the disturbance frequency of the work environment will be studied in order to find out the resonant source and avoid the resonant frequency.

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