Dynamic Characteristics Analysis of Two-Beam Laser Welding Robot for Fulselage Panels

Qingfei Zeng

Tongji University

Xuemei Liu (✉ liuxuemei@tongji.edu.cn)

Tongji University <https://orcid.org/0000-0002-3965-6539>

Ziru Liu

Tongji University

Aiping Li

Tongji University

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Dynamic characteristics analysis of two-beam laser welding robot for fuselage panels

Qingfei Zeng, Xuemei Liu*, Ziru Liu, Aiping Li

School of Mechanical Engineering, Tongji University, Shanghai 201804, China

* Corresponding author. Tel.: +86-18521354437. E-mail address: liuxuemei@tongji.edu.cn

Abstract—Industrial robotics is becoming increasingly popular in the field of manufacturing automation. Two-beam laser welding robot which is a proprietary industrial robot of great importance to improve the welding quality of stringer-skin T-shape structure. In the process of two-beam laser cooperative welding, the robot constantly adjusts its own posture, and the position and posture of each joint would change simultaneously, which leads to the change of the natural frequency, and other dynamic characteristics of the welding robot. Based on the finite element method (FEM), the modal analysis of the robot joints in the range of motion ability and the range of motion in the process of two beam laser welding are studied, which can provide the basis for the design and accurate control of the robot with high degree of freedom (DOF). The dynamic characteristics of the whole robot in different positions and attitudes is carried out, which includes two parts, one is importance ranking of 18 joints of the robot through orthogonal test according to the range of each joint movement. The other is obtaining a plurality of time points in one welding cycle, and performing a modal analysis of the robot at each time point on the basis of the robot joints in the range of motion during the process of two-beam laser welding, the optimal number of time nodes are attained and the test workload could be reduced. The approach described herein provides a theoretical basis for robotics design and control optimization.

Keywords—Two-beam laser welding robot; Dynamic characteristics; Modal analysis; Natural Frequency

I. INTRODUCTION

With ongoing advancements in robotics, robotic welding has gained popularity in industries as it reduces human intervention in hazardous and unpleasant working environment^[1]. Especially, welding robots are widely used for most welding works in manufacturing industries due to their efficient and accurate operation. As the need for precise joining of welding components of fuselage panels increases, so does the need to reduce welding distortion in laser welding. Two-beam laser welding has been paid more and more attention in aviation field, because it is an advanced process for precise, low distortion joining of manufacturing parts^[2]. During the application of industrial robot to two-beam laser welding, in addition to good reliability and suitable workspace, the overall structure of industrial robot also needs well dynamic performance^[3-5], which will directly affect the stability, reliability and accuracy of the robot. Performance of industrial robots is limited due to their mechanical structure involving rotational joints with a lower stiffness. Commonly, vibration instabilities are more likely to appear in industrial robots than in parallel robots and conventional machine tools^[6]. Good dynamic characteristics can improve the ability of the robot to cope with time-varying load, and avoid the occurrence of malignant vibration to a certain extent. Measuring the dynamic characteristics of the robot is the premise of its modeling, analysis and accurate control. Experience and repeated measurement are the main means in traditional structural modification of the robot, which greatly slows down the design speed, increases the design cost, and it is difficult to achieve the optimal design quality. Using FEM in modal analysis^[7-8] has important reference value for the dynamic performance, for example, the stiffness^[9-11], which is really essential to evaluate structural design and improve design in time.

For other dynamic characteristics of robots, such as modal parameters, including natural frequency and corresponding mode shape, etc., a considerable amount of theoretical and experimental research has been carried out from various perspectives. A main focus of the research is the establishment of basic theoretical model analysis. In a semi-analytical approach^[12], the equations of limbs within the 5-DOF parallel mechanism are first formulated by FEA and then reduced to super-element models to establish the dynamic model of entire system and estimate the lower-order natural frequencies of the robot. An analytical approach based on the matrix structure formulation with Lagrange multipliers for model simplification is presented by Nguyen et al.^[13]. This approach takes into account all structural parameters and allows both of static and dynamic characterization of the robot. Modal frequency of the 6-DOF parallel robot is identified and mapped in its Cartesian workspace. Formulation of the motion equations for a multi-link robot consisting of the revolute joints, and the prismatic joints is challenging. The finite element kinematic and dynamic formulation for the robot included the revolute joints, the fixed

prismatic joints and the sliding prismatic joints was successfully developed and validated^[14]. Kumar^[15] develops a dynamic model of a rotating Cartesian manipulator under prismatic motion to explore the effect of generic payload and externally applies asymmetric load on the calculation of modal parameters and dynamic performance of a rotating manipulator.

On account of the basic theory for modal analysis, a large number of scholars have completed modal analysis with variety simulation softwares. Inputting sine sweep signal on a 6-DOF spot-welding robot end effector, the coupling vibration system of the robot is established to optimize the design of the robot by Luo et al.^[16] in ADAMS/Vibration with former generated modal neutral file in ANSYS. Lv and Yang^[17] discussed the structural stability of 4-DOF manipulator, which is suitable for welding spot of three-dimensional space concentrated distribution and approximate single-axis distribution in car body. By using the UG/CAE module, analysis is applied to the main structure of the manipulator, and the results show that the whole structure meets the design requirement of stiffness and strength. The lanczos eigensolver and two different element types of Abaqus/CAE are used to calculate the modal characteristics of a two-link flexible manipulator after establishing the dynamic equations^[18]. Guo et al.^[19] carried out the modal analysis of the critical components included circular middle plate and leg brackets of an amphibious spherical robot. Using ANSYS WORKBENCH software, parts models were incorporated into the robot design to determine the natural frequencies and the associated mode shapes of the first six orders.

On the basis of detailed theoretical analysis and simulation calculation, some scholars made a detailed analysis of the calculation results, and got the conclusion that it is helpful to improve the mechanical structure performance. The natural frequencies and mode shapes of four-bar linkages and its variants are estimated by modal analysis, whereas the dynamic performance at different operating regimes is assessed^[20]. By establishing the improved analytical dynamic model based on the Energy principle, Hamilton principle and the multipoint constraint equations of the micro-manipulator, Yuan et al.^[21] carries out the modal analysis to get the free vibration expression of the manipulator. Then, the natural frequency of the micro-manipulator with other design objectives of the manipulator are coordinated to make the overall performance better. More and more scholars use the dynamic performance obtained from the modal analysis to improve the design of robots or their components. Through the establishment of the finite element model and modal analysis for end effector mounting bracket on palletizing robot, the mass of the end effector is reduced and the first natural frequency is increased meanwhile^[22], which improves the dynamic performance of robotic system and reduces energy consumption. Building a 3D model of demolition robot in SolidWorks. Li et al.^[23] improves the layout of the structure and structural rigidity of the robot to ameliorate its dynamic characteristics according to the simulation results of modal analysis. Combining Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA), the robot frequency response functions as a function arm configuration are determined^[24]. This approach is successfully applied to optimize the sampling density and robot downtime of the designed arm.

In these studies, many researchers paid attention to the natural frequencies and the modal of the robot parts, but the overall dynamic performance of the robot in the process of operation has rarely been mentioned. What's more, the DOF of the robot as the research object is also relatively low in these studies, and the dynamic characteristics of the high degree of freedom welding robot will have a great impact on its work quality. In particular, the large-scale cooperative robot for two-beam laser welding has a higher DOF than the general industrial robot or the same type of robot in order to complete the precision welding of bilateral welds. The higher the DOF of the robot, the more flexible the robot system is, and the more complex the configuration sets of the robot are. In the process of two-beam laser cooperative welding robot motion, end effectors and joints of the robot change their PAA (position and attitude) constantly, which makes the natural frequency of the robot system change with the change of the whole robot PAA. Therefore, only in the initial state or a certain instantaneous state, the natural frequency of robot system could not be clearly defined as the natural frequency of robot system. Through modal analysis of the whole robot in different positions and attitudes, the natural frequencies and vibration modes can be obtained, so as to find out the relatively weak links in the robot, which provides a method for the prediction and evaluation of the dynamic characteristics of cooperative two-beam laser welding robot for stringer-skin T-shape structure in the aviation field, it would provide a theoretical basis for the structure improvement of the robot.

It will be a very complicated work to analyze the natural frequencies of two-beam laser cooperative welding robot in all the PAA in the whole workspace. To solve this problem, the dynamic characteristics of two-beam laser welding robot based on finite element analysis are studied in two new aspects including importance ranking of 18 joints of the robot and the optimal number of time nodes in this paper. The structure of this paper is as follows: In Sect.2, a 3D model of the two-beam laser cooperative welding robot, especially the manipulators of the robot are presented along with basic theories for the modal analysis. Using finite element analysis software ANSYS WORKBENCH, configuration-dependent modal analysis of the robot are presented in Sect.3. Modal analysis of the robot according to a plurality of time points in one two-beam laser welding cycle is given in Sect.4. Sect.5 provides a summary and discusses the direction of future work in this field.

II. TWO-BEAM LASER WELDING ROBOT

2.1 Basic structure of two-beam laser welding robot

When two-beam laser welding is carried out for aircraft fuselage panels, the welding equipment should have high degree of freedom movement ability, so as to ensure that the laser welding joint can move accurately with the weld trajectory and complete the laser welding for typical AL-LI (aluminum-lithium) T-joints of fuselage panels. For the two-beam laser welding robot studied in this paper, three manipulators is mounted on a 3-DOF gantry at the certain angle to obtain a reasonable workspace to complete the cooperative welding, as shown in Fig. 1 The left and right manipulator of the robot is used to weld the bilateral three-dimensional seams formed by the stringer and the skin of T-joints, and the middle manipulator is used to press the stringer to improve the welding quality, as shown in Fig. 2.

Fig 1. Installation of three manipulators

Fig 2. Manipulators with different functions

Compared to general industrial manipulators, the end effectors of two-beam laser welding robot could be scaled to larger proportions easily in Cartesian coordinate as the 3-DOF gantry in robot could complete large range of 3-DOF motion. The Cartesian coordinate robot's relatively straight forward operation make it highly desirable in manufacturing. Because the individual axes can be easily replaced, downtime is reduced, and maintenance costs are kept to a minimum. In addition, the entire system can be disassembled into its component parts for use in multiple single-axis applications. The traditional analysis method simplifies the robot structure to regular beam and rod structure, which is not suitable for the gantry type robot with multiple suspended manipulators because of its complex components. The dynamic characteristics such as natural frequency of cooperative welding robot with multiple manipulators will greatly affect the laser welding quality of AL-LI T-joints for aircraft fuselage panels.

2.2 Basic theories of the modal analysis

The basic idea of modal analysis is to decouple the matrix equation describing the dynamic performance of the structure, so that the modal parameters describing the dynamic characteristics of the structure, such as natural frequency, modal shape, modal mass, modal stiffness and modal damping ratio, among which the most important modal parameters are natural frequency and modal shape, could be determined. Above all, the purpose of natural frequency characteristic is to calculate modal parameters, which could not only avoid resonance and harmful vibration mode, but also provide necessary data for dynamic response analysis.

If the overall stiffness performance of the robot system is poor, flutter phenomenon would be produced by robot self-excitation during the actual welding. According to the basic modal theory, the motion differential equation of the robot system is described as follows:

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

Where $[\mathbf{M}]$ is mass matrix, $[\mathbf{C}]$ is damping matrix, $[\mathbf{K}]$ is stiffness matrix, $\{\ddot{\mathbf{X}}\}$, $\{\dot{\mathbf{X}}\}$, $\{\mathbf{X}\}$ are vibration acceleration vector, velocity vector and displacement vector respectively, $\{\mathbf{X}\} = \{X_1, X_2, \dots, X_n\}^T$; $\{\mathbf{F}(t)\}$ is the applied time-varying nodal load vector, $\{\mathbf{F}(t)\} = \{F_1, F_2, \dots, F_n\}^T$, and t is the corresponding time.

Without external force, $\{\mathbf{F}(t)\} = 0$, the damping term is omitted at the same time, the motion differential equation of robot in undamped free vibration can be obtained:

$$[\mathbf{M}]\{\ddot{\mathbf{X}}\} + [\mathbf{K}]\{\mathbf{X}\} = \{0\} \quad (2)$$

Since $\{\mathbf{X}\} = [\phi]\{\mathbf{y}\}$, $\{\mathbf{X}\}$ can be linearly changed to $\{\mathbf{y}\}$, where $[\phi]$ is transition matrix. At the same time, $\{\ddot{\mathbf{X}}\} = [\phi]\{\ddot{\mathbf{y}}\}$. Taking $\{\mathbf{X}\}$ and $\{\ddot{\mathbf{X}}\}$ into formula (2), equation (3) can be changed to the following:

$$[\mathbf{M}^*]\{\ddot{\mathbf{y}}\} + [\mathbf{K}^*]\{\mathbf{y}\} = \{0\} \quad (3)$$

Where $[\mathbf{M}^*]$ is generalized mass matrix, $[\mathbf{K}^*]$ is generalized stiffness matrix. The motion equation (4) of the i th degree of freedom can be obtained from equation (3).

$$\ddot{y}_i + \omega_i^2 y_i = 0 \quad (4)$$

Where ω_i is the frequency of the vibration system in the i th mode. By solving the above equation, it is obtained that $y_i(t) = A_i \sin \omega_i t + A_i^* \cos \omega_i t$, where A_i and A_i^* are determined by $x_i(0)$ and $\dot{x}_i(0)$.

Multiply both sides of equation (2) by $[\mathbf{M}]^{-1}$, then,

$$[\mathbf{I}]\{\ddot{\mathbf{X}}\} + [\mathbf{D}]\{\mathbf{X}\} = \{0\} \quad (5)$$

Where $[\mathbf{I}]$ is eye matrix, $[\mathbf{D}]$ is the transition matrix.

If $\{\mathbf{X}\} = \{\mathbf{A}\}e^{i\omega t}$, equation (5) can be modified to the following form:

$$\{\ddot{\mathbf{X}}\} = -\omega^2 \{\mathbf{A}\}e^{i\omega t} = -\lambda \{\mathbf{X}\} \quad (6)$$

Where $\lambda = \omega^2$, we obtain the following:

$$[[\mathbf{D}] - \lambda[\mathbf{I}]]\{\mathbf{X}\} = \{0\} \quad (7)$$

From the known vector, a non-zero solution can be obtained, namely $[[\mathbf{D}] - \lambda[\mathbf{I}]] = \{0\}$, the natural frequency of the robot ω_i can be obtained by calculating the eigenvalue.

III. CONFIGURATION-DEPENDENT MODAL ANALYSIS OF THE ROBOT

Different configuration of the high DOF two-beam laser welding robot has different natural frequency. It is impossible to measure the natural frequency information of the two-beam laser welding robot in all positions and postures as all joints of the robot moving in the continuous space. Even if the joint motion space of 18 robot joints is discretized, the number of experiments is still too tremendous. To solve this problem, it is necessary to obtain the working space of the robot by analyzing the working objects and structural parameters of the welding robot^[25] first. Then the joint motion space in welding state is further obtained through the robot working space. What's more, it is essential to select a series of the joints movement scientifically based on the experimental design method. In this paper, the orthogonal experimental method is used to design

the level and characteristics. Through the modal analysis of the whole robot system, the natural frequency and mode shape of the whole robot is obtained, and then the importance sequence of joints is analyzed. The analysis flowchart is shown in Fig. 3.

Fig. 3 Flowchart

3.1 Robot joint motion samples

A numerical model of the two-beam laser welding robot has been developed by means of ANSYS Workbench®, a finite element commercial software. Besides the typical tools of a standard FEM software, such as the definition of the material, the type of elements, the mesh attributes and the kinematic joints of the robot have been modeled. A model built in this way allows to modify the configuration of the joints where the vibrational behavior has to be analyzed. The motion ability of each joint of two-beam laser welding robot is different. The maximum motion ranges of the 18 joints are listed in Table 1. J_{11} , J_{12} , J_{13} stand for the motion of gantry with 3 DOF. J_{14} , J_{15} , J_{16} stand for the rotation of the three revolute joints of pressing manipulator. J_{21} , J_{22} , J_{23} , J_{24} , J_{25} , J_{26} stand for the rotation of the six revolute joints of left manipulator. J_{31} , J_{32} , J_{33} , J_{34} , J_{35} , J_{36} stand for the rotation of the six revolute joints of right manipulator.

Table 1. The range of each joint

J_{ij}	Min &Max	Magnitude
J_{11}	$\pm 2500\text{mm}$	5000mm
J_{12}	$\pm 1500\text{mm}$	3000mm
J_{13}	$\pm 500\text{mm}$	1000mm
J_{14}	$\pm 350^\circ$	700°
J_{15}	$\pm 125^\circ$	250°
J_{16}	$\pm 350^\circ$	700°
J_{21}	$\pm 185^\circ$	370°
J_{22}	-65° to 125°	190°
J_{23}	-220° to 64°	284°
J_{24}	$\pm 350^\circ$	700°
J_{25}	$\pm 130^\circ$	260°
J_{26}	$\pm 350^\circ$	700°
J_{31}	$\pm 185^\circ$	370°
J_{32}	-65° to 125°	190°
J_{33}	-220° to 64°	284°
J_{34}	$\pm 350^\circ$	700°
J_{35}	$\pm 130^\circ$	260°
J_{36}	$\pm 350^\circ$	700°

In the actual welding process, the configuration of the joints has a significant influence on the two-beam laser welding robot dynamic performance. When the two-beam laser welding robot with multiple manipulators welds bilateral seam of T-joint, the schematic diagram of the end effector operation is shown in Fig. 4. According to the geometric constraints of T-joint and inverse kinematic model of the robot^[26], the displacement or rotation angle of all joints of the robot can be calculated according to equation (8), and the solution obtained here will be unique.

$$\Theta(J_{i,j}) = \Gamma^{-1}(T_i) \quad (8)$$

Fig. 4 Welding bilateral seam of stringer-skin T-shape structure

Table 2. The range of each joint movement during two-beam welding

J_{ij}	Max	Min
J_{11}	199.3764mm	123.9015mm
J_{12}	-856.8880mm	-856.9184mm
J_{13}	-422.9694mm	-438.1956mm
J_{14}	140.4473°	139.3514°
J_{15}	14.5417°	14.2081°
J_{16}	38.6615°	39.7920°
J_{21}	-14.6705°	-14.6762°
J_{22}	77.5184°	77.5114°
J_{23}	-3.5329°	-3.4702°
J_{24}	-6.0515°	-6.4493°
J_{25}	-81.6963°	-81.5704°
J_{26}	-25.0257°	-24.9512°
J_{31}	13.0076°	12.9712°
J_{32}	76.0737°	75.6411°
J_{33}	-11.6426°	-11.5865°
J_{34}	-4.6566°	-4.2540°
J_{35}	-55.2206°	-55.0879°
J_{36}	28.8611°	28.7361°

The range of motion of the joints can be greatly narrowed according to the working posture, which makes the sample data more accurate. New motion ranges of the 18 joints during the operation of two-beam laser welding are listed in Table 2. Based on the forward kinematics model of two-beam laser robot with multiple manipulators, the end pose of the robot is obtained according to equation (8) and the displacement or rotation angle of all joints of the robot. Correspondingly, various configurations of the robot during the two-beam laser welding are also available.

$$T_i = \Gamma(\Theta(J_{i,j})) \quad (9)$$

Where T_i ($i=1,2,3$) stand for the PAA of robot end effector, $\Theta(J_{ij})(i=1,2,3; j=1, \dots, 6)$ stand for the displacement or rotation angle of all joints.

The motion of each joint brings the end effectors of the two-beam laser welding robot in the specific PAA inside the workspace, which is shown in Fig. 5. The difference between robot joints in different PAA is not obvious due to the geometric dimension of the robot truss and requirement of two-beam laser welding. The obvious difference could be seen from the PAA of the robot three end effectors in the red circle in Fig. 5.

Fig. 5 Comparison of the robot joints in different PAA

Orthogonal array is widely used in multiple factor optimization experiments ^[27-29]. In our orthogonal experiment, factors are movement of 18 joints. Considering the range of each joint movement during two-beam laser welding process, movement of 7 joints is minimal, while the movement of other 11 joints is large. Accordingly, there are 11 three-level factors and 7 two-level factors in this experiment. A mixing standard orthogonal experiment $L_{36}(2^7 \times 3^{11})$ is designed as shown in Table 3. The orthogonal experiments were conducted to study the influence of joints motion on the robot natural frequency.

Table 3. Design of experiment*

Experiment Number	J_{11}	J_{12}	J_{13}	J_{14}	J_{15}	J_{16}	J_{21}	J_{22}	J_{23}	J_{24}	J_{25}	J_{26}	J_{31}	J_{32}	J_{33}	J_{34}	J_{35}	J_{36}
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	2	1	2	2	2	2	1	1	1	2	2	2	1	1	1	2	2	2
3	3	1	3	3	3	3	1	1	1	3	3	3	1	1	1	3	3	3
4	1	1	1	1	1	2	1	1	1	2	2	2	1	2	2	3	3	3
5	2	1	2	2	2	3	1	1	1	3	3	3	1	2	2	1	1	1
6	3	1	3	3	3	1	1	1	1	1	1	1	1	2	2	2	2	2
7	1	1	1	2	3	1	1	2	2	2	3	3	2	1	1	1	2	2
8	2	1	2	3	1	2	1	2	2	3	1	1	2	1	1	2	3	3
9	3	1	3	1	2	3	1	2	2	1	2	2	2	1	1	3	1	1
10	1	2	1	3	2	1	2	1	2	3	2	3	2	1	2	2	1	3
11	2	2	2	1	3	2	2	1	2	1	3	1	2	1	2	3	2	1
12	3	2	3	2	1	3	2	1	2	2	1	2	2	1	2	1	3	2
13	1	2	2	3	1	3	2	2	1	2	1	3	2	2	1	3	2	1
14	2	2	3	1	2	1	2	2	1	3	2	1	2	2	1	1	3	2
15	3	2	1	2	3	2	2	2	1	1	3	2	2	2	1	2	1	3
16	1	2	2	3	2	1	2	2	2	1	3	2	1	2	2	3	3	2
17	2	2	3	1	3	2	2	2	2	2	1	3	1	2	2	1	1	3
18	3	2	1	2	1	3	2	2	2	3	2	1	1	2	2	2	2	1
19	1	1	2	1	3	3	1	2	2	3	1	2	1	1	2	2	1	2
20	2	1	3	2	1	1	1	2	2	1	2	3	1	1	2	3	2	3
21	3	1	1	3	2	2	1	2	2	2	3	1	1	1	2	1	3	1
22	1	1	2	2	3	3	1	2	1	1	2	1	2	2	2	1	3	3
23	2	1	3	3	1	1	1	2	1	2	3	2	2	2	2	2	1	1
24	3	1	1	1	2	2	1	2	1	3	1	3	2	2	2	3	2	2
25	1	1	3	2	1	2	1	1	2	3	3	1	2	2	1	3	1	2
26	2	1	1	3	2	3	1	1	2	1	1	2	2	2	1	1	2	3
27	3	1	2	1	3	1	1	1	2	2	2	3	2	2	1	2	3	1
28	1	2	3	2	2	2	2	2	1	1	1	3	1	1	1	2	3	1
29	2	2	1	3	3	3	2	2	1	2	2	1	1	1	1	3	1	2

30	3	2	2	1	1	1	2	2	1	3	3	2	1	1	1	1	2	3
31	1	2	3	3	3	2	2	1	2	3	2	2	1	2	1	1	2	1
32	2	2	1	1	1	3	2	1	2	1	3	3	1	2	1	2	3	2
33	3	2	2	2	2	1	2	1	2	2	1	1	1	2	1	3	1	3
34	1	2	3	1	2	3	2	1	1	2	3	1	2	1	2	2	2	3
35	2	2	1	2	3	1	2	1	1	3	1	2	2	1	2	3	3	1
36	3	2	2	3	1	2	2	1	1	1	2	3	2	1	2	1	1	2

*1 represents the minimum value within the range of the robot joint motion, 2 represents the median value within the range of the robot joint motion, and 3 represents the maximum value within the range of the robot joint motion.

3.2 Modal analysis

The level of detail of the mesh is the result of a sensitivity analysis where the size of the elements was refined until the results of the simulations stabilized. The model includes about 281000 elements and 1046000 nodes globally. Fig. 6 shows some mesh details of the principal parts of the model.

Fig. 6 Mesh details

Modal parameters such as natural frequency and mode shape can be obtained after modal analysis. The distribution range of natural frequency and the shape of vibration modes of the two-beam laser welding robot are studied. As there are fewer nodes corresponding to the main vibration at lower frequency, it is more dangerous than the main vibration at higher frequency. The resonance frequency of multi-DOF robot system is mainly in the low frequency band. The first six modes of the whole model of the multi arm welding robot are extracted, which can basically meet the requirements of the research on the dynamic characteristics of the industrial robot. The modal shape can describe the shape of each order modal vibration, and the final modal shape value needs to be expressed by displacement, which is often called displacement mode. The solution is achieved by the standard ANSYS and former six modes have been stored on a standard PC (Intel(R) Xeon(R) W-2135 CPU@3.70 GHz, 16 GB RAM). A certain set of joints motion in the Table 2 is selected, and former six-order mode shapes of the two-beam laser welding robot are shown in Fig. 7.

(a) First and second-order mode

(b) Third and fourth-order mode

(c) Fifth and sixth-order mode

Fig. 7 Modal of welding robot

After analyzing orthogonal test results of variance, the ranking effect of each joint motion on the dynamic performance of the robot system is listed in Table 4 and Table 5. According to the order effect, it can be seen that prismatic joints J_{11} and J_{13} motion have greatest influence on the robot natural frequency among all joints motion. Moreover motion of the rotate joints J_{14} , J_{15} , J_{16} , J_{24} , J_{25} , J_{26} , J_{34} , J_{35} , J_{36} on manipulators forearm significantly affected the robot natural frequency and motion of the rotate joints J_{21} , J_{22} , J_{23} , J_{31} , J_{32} , J_{33} on upper arm was not significant during the two-beam welding process. The main joints that affect the natural frequency of the robot in the process of two beam laser welding are obtained. Precedence of robot joints could be established by order of importance, which helps to adjust the setting of control parameters in the case of errors at the end of the robot. The analysis and experimental results can further provide a reference for the use of the two-beam laser welding robot in practical applications or the optimization of the configuration design.

Table 4. Ranking of 9 joints*

Level	J_{12}	J_{21}	J_{22}	J_{23}	J_{31}	J_{32}	J_{33}	J_{11}	J_{13}
1	19.56	19.48	19.56	19.56	19.48	19.48	19.56	17.03	19.54
2	19.48	19.56	19.48	19.48	19.56	19.56	19.49	20.58	19.44
3	/	/	/	/	/	/	/	20.96	19.58
Delta	0.08	0.07	0.07	0.07	0.07	0.07	0.07	3.93	0.14
Ranking	12	17	14	15	13	16	18	1	2

*1 represents the minimum value within the range of the robot joint motion, 2 represents the median value within the range of the robot joint motion, and 3 represents the maximum value within the range of the robot joint motion. Delta measures the size of the effect by taking the difference between the highest and lowest characteristic average for a factor.

Table 5. Ranking of the other 9 joints*

Level	J_{14}	J_{15}	J_{16}	J_{24}	J_{25}	J_{26}	J_{34}	J_{35}	J_{36}
1	19.45	19.56	19.56	19.56	19.45	19.56	19.56	19.45	19.56
2	19.56	19.56	19.56	19.56	19.56	19.45	19.45	19.56	19.45
3	19.56	19.45	19.45	19.45	19.56	19.56	19.56	19.56	19.56
Delta	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Ranking	11	5	6	3	7	10	4	8	9

*1 represents the minimum value within the range of the robot joint motion, 2 represents the median value within the range of the robot joint motion, and 3 represents the maximum value within the range of the robot joint motion. Delta measures the size of the effect by taking the difference between the highest and lowest characteristic average for a factor.

IV. MODAL ANSYS OF WELDING PROCESS AT EACH TIME POINT

According to order effect of each joint on robot natural frequency is one aspect of studying the dynamic performance of the robot, and it is necessary to study the dynamic performance of robot from the time dimension. The more discrete time points, the more accurate the robot mode curve with time, but it will also lead to a surge of workload. Through the inverse kinematic analysis, 18 joints movement of two-beam welding robot at 51 time nodes could be obtained, which is shown in Table 6.

Table 6. The movement of each joint during two-beam laser welding*

J_{ij}	1	2	...	50	51
J_{11}	199.3764mm	123.9015mm	...	-3542.8114	-3618.4501mm
J_{12}	-856.8880mm	-856.9184mm	...	-856.9588	-857.3035mm
J_{13}	-422.9694mm	-438.1956mm	...	-459.3181	-625.0085mm
J_{14}	140.4473°	139.3514°	...	40.6486	39.5527°
J_{15}	14.5417°	14.2081°	...	14.2081	14.5417°
J_{16}	38.6615°	39.7920°	...	140.2080	141.3386°
J_{21}	-14.6705°	-14.6762°	...	-15.1418	-15.1456°
J_{22}	77.5184°	77.5114°	...	77.0279°	77.0194°
J_{23}	-3.5329°	-3.4702°	...	-1.3883°	-1.3692°
J_{24}	-6.0515°	-6.4493°	...	-26.9781°	-27.4018°
J_{25}	-81.6963°	-81.5704°	...	-74.8979°	-74.7612°
J_{26}	-25.0257°	-24.9512°	...	-20.0504°	-19.9226°
J_{31}	13.0076°	12.9712°	...	11.6667°	11.6380°
J_{32}	76.0737°	75.6411°	...	76.0578°	75.6311°
J_{33}	-11.6426°	-11.5865°	...	-9.3713°	-9.3417°
J_{34}	-4.6566°	-4.2540°	...	17.6617°	18.1284°
J_{35}	-55.2206°	-55.0879°	...	-48.9228°	-48.8160°
J_{36}	28.8611°	28.7361°	...	20.8028°	20.6120°

*... represents each joint movement at time node 3 to 49.

We systematically obtained a plurality of time points in one welding cycle and performed the modal analysis of the robot at each time point. Specifically, in one welding cycle of T-joint, 3 time nodes, 6 time nodes, 11 time nodes and 26 time nodes are selected respectively to carry out modal analysis of the robot under each time node.

With the continuous movement of the robot joint, the main frequency curve of the robot under 3 time nodes and 6 time nodes is shown in Fig. 8 and Fig. 9. We can see from the figure that when there are few time nodes, such as 3 time nodes, the fitted curve is very inaccurate. Although it can reflect the general trend, it could not reflect the specific fluctuation of the robot natural frequency during the whole welding process.

Fig. 8 Three time nodes

Fig. 9 Six time nodes

There are obvious differences in the natural frequency curve of the robot when 3 time nodes and 6 time nodes are selected, which indicates that it is not in line with the reality to describe the natural frequency curve of the robot only by taking three time nodes. The more nodes are selected, the closer the natural frequency curve is to the real change process. Increasing the time nodes to 11 and 26, the change curve of 11 times nodes is basically the same as the curve of 26 times nodes as shown in Fig. 10 and Fig. 11, which shows that the change process and extreme value of the natural frequency of the two beam cooperative welding robot can be basically expressed when the number of time nodes is 11.

Taking 3 and 6 time nodes could not completely describe the natural frequency curve of the two-beam laser welding robot. With the increase of the number of time nodes to 11, the stress curve is basically the same as taking 26 nodes.

Fig. 10 Eleven time nodes

Fig. 11 Twenty-six time nodes

V. CONCLUSION

Considering the different PAA of the two-beam laser robot, the modal analysis of the robot is carried out from the following two aspects, and the corresponding conclusions are obtained.

In this article, the analysis samples are constructed by orthogonal experimental design method, and the range analysis and variance analysis are carried out on the experimental results to determine the test level and test parameters. The natural frequencies and corresponding mode shapes of the former six orders for the two-beam laser welding robot were found. The order of robot joint's importance in welding operation is given by combining theoretical analysis with simulation experiment, which enables an insight into accurate control of robot motion process and scientific adjustment of motion error.

For the time node method, the natural frequencies of robot on the dynamic characteristic of its natural frequency during the two-beam laser welding operation is calculated. The natural frequency curve drawn from 11 time nodes is the most reasonable description of the dynamic characteristics of the robot in case of that too few nodes could not reflect the real changes, too many nodes increase the workload. Thus, the approach in this paper provides a reliable reference for future structural design and optimize control of robots.

AUTHOR CONTRIBUTION

Qingfei Zeng wrote the first draft of the paper. All authors revised and approved the final version of the manuscript.

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AVAILABILITY OF DATA AND MATERIALS

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

DECLARATIONS

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