Proceedings of the 2011 IEEE International Conference on
Cyber Technology in Automation, Control, and Intelligent Systems
March 20-23, 2011, Kunming, China

Rigid-Flexible Coupling Dynamics Analysis of A Spot-Welding Robot

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Abstract—**This paper studied a dynamics simulation analysis method for a rigid-flexible coupling system of spot-welding robot. The 6R spot-welding robot multi-body dynamics model is created by FEA (finite element analysis) and MBD (multi-body dynamics) software. Based on rigid-flexible coupling analysis method, we analyze mechanics characteristic of upper arm and get the deformation of end measuring point, maximum stress position and stress curve, when spot-welding robot is moving under loads. The analysis method is intuitional and accurate, and can increase the accuracy of dynamic response analysis of parts under the dynamic loads. The simulation results are very important theoretical basis for structure design and optimization of the spot-welding robot.**

Keywords-Rigid-flexible coupling dynamics; FEA; Spot-welding robot; ANSYS-ADAMS

I. Introduction

Mechanical systems are generally composed by several objects, which are jointed as one body through a series of geometric constraints to complete intended actions. Therefore, the entire mechanical system can be called multi-body system [1]. If we regard each object as non-deformable rigid body, the system is called multi-rigid-body system; if we must take account of their deformation, the system is called multi-flexible-body system or flexible-multi-body system [2].

In traditional design method, the components of mechanical system are always considered as rigid-body movement without considering the elastic deformation. Therefore, it can not reflect the coupling relationships between rigid body motion and elastic deformation, and then mechanical properties of components are also not true. However, multi-flexible-body system dynamics researched the interaction or coupling as well as the unique dynamic effect caused by coupling [3-7]. Applying modeling theory and theory of multi-flexible-body system dynamics, it can realize precise modeling, virtual design, performance optimization, system matching, and performance prediction and so on.

In recent years, flexible-body simulation has become a research hotspot in simulation field. It has been widely used in the mechanics, aviation, shipbuilding and other industry. In mechanical systems, flexible body has an important influence to its movement. When computing kinematics analysis, it will give rise to a great error without considering the impact of flexible body. Conversely, the motion of the whole system determines the motion state and force status of each component. It also determines the stress and strain distribution within the component [8-11]. Therefore, this kind of co-simulation method by using ANSYS and ADAMS software emerged as the times require. It can not only accurately simulate the movement of the entire system, but also do stress and strain analysis for the flexible body of system based on the result of kinematics simulation.

In this paper, modal neutral file (.mnf file) is generated by using finite element software ANSYS, which contains the flexible body mass, center of mass, inertia, frequency and mode shape information about upper arm of the spot welding robot. And then in the multi-body dynamics software ADAMS, rigid robot upper arm will be replaced with a flexible body to perform the following dynamic analysis [12]. We select three typical configurations for dynamic stress and deformation analysis. By comparing the displacement and stress data under the different configurations, we can learn about the mechanical characteristic of the whole robot.

The rigid-flexible coupling multi-body model established by this method can more accurately analyze the dynamic characteristics of machine.

II. Establishment of Computational Model on Flexible-body

Multi-body system dynamics model can be created by using a variety of mechanical principles, including the energy conservation law, Newton-Euler equation, Lagrange equation, Hamilton principle, Kane equation and so on. Lagrange equation which is established based on the point of energy, the advantage is to facilitate the program procedures and easy to build forward or inverse kinematics models [13]. Besides, we can also easily achieve the dynamic modeling of recursive form and add the control feedback. Lagrange equation modeling approach is more mature and this modeling method is used in many multi-body system analysis softwares. ADAMS software used in this article is like that.

A. Generalized coordinate on flexible-body

Flexible body can be viewed as a collection of nodes of finite element model, and the deformation can be seen as a linear superposition of mode shapes. As see the Fig.1, point P is a node on flexible body, point P' is the deformed position for the flexible body, point B is the coordinate system of flexible body and point G is the basic coordinate system.

This work was supported by the National Science and Technology Major Project on High Grade CNC Machine Tool and Fundamental Manufacturing Equipment under Grant 2009ZX04013.

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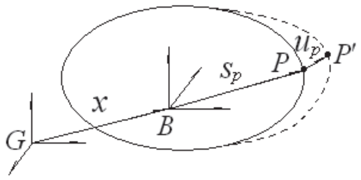


Figure 1. Moving schematic of flexible-body on node P

Under the basic coordinate system G, the position of point B is

$$\vec{x} = (x, y, z), \tag{1}$$

and its direction expressed by Euler angles is

$$\vec{\psi} = (\varphi, \theta, \psi). \tag{2}$$

Modal coordinates is

$$\vec{q} = \{q_1, q_1, ..., q_M\}^T, \tag{3}$$

where M is the number of modal coordinates, so the flexible body generalized coordinates is

$$\vec{\xi} = \{x\ y\ z,\ \ \varphi\ \theta\ \psi,\ \ q_i (i = 1, ..., M)\}^T = \{\vec{x}\ \vec{\psi}\ \vec{q}\}. \tag{4}$$

B. Differential equations of motion of flexible body

Flexible body position vector of node P can be expressed as:

$$\vec{r}_p = x + {}^G_B A (s_p + u_p), \tag{5}$$

where, ${}^G_B A$ —transformation matrix of coordinate system B relative to coordinate system G;

s_p —position of point P under coordinate system B when body is non-deformed;

u_p —direction vector of point P' on deformed body with respect to point P on non-deformed body;

Here, $u_p = \Phi_p q$ and Φ_p is modal matrix subblock for motion degree-of-freedom on node P'.The Velocity of node P is:

$$\vec{v}_p = \left[I - {}^G_B A (\tilde{s}_p + \tilde{u}_p) B\, {}^G_B A \Phi_p \right] \dot{\xi}. \tag{6}$$

Where, tilde indicates the position vector is non-symmetrical matrix; matrix B is defined as first-order derivative of Eulerian angle relative to time or angular velocity transition matrix. So the kinetic and potential energy can be expressed as:

$$T = \frac{1}{2} \int_v \rho v^T v dV = \frac{1}{2} \dot{\xi}^T M(\xi) \dot{\xi}, \tag{7}$$

$$V = V_g(\xi) + \frac{1}{2} \xi^T K \xi. \tag{8}$$

Establish the differential equation of motion of flexible body using Lagrange multipliers method:

$$M\ddot{\xi} + \dot{M}\dot{\xi} - \frac{1}{2}\left[\frac{\partial M}{\partial \xi}\dot{\xi}\right]^T + K\xi + f_g + D\dot{\xi} + \left[\frac{\partial \Psi}{\partial \xi}\right]^T \lambda = Q. \tag{9}$$

Here, K —modal stiffness matrix;

D —modal damping matrix;

f_g —generalized gravity;

Q —generalized external force;

λ —Lagrange multiplier of constraint equation;

Among them, $\dot{\xi}$ and $\ddot{\xi}$ are the first-order and second-order derivative of flexible-body generalized coordinates relative to time; M and $\dot{M}$ are the flexible-body mass matrix and its time derivative; $\partial M / \partial \xi$ is the partial derivative of flexible-body mass matrix relative to its generalized coordinates. It is a $(M+6)^3$ dimensional tensor and M dimension mode.

III. ESTABLISHMENT OF DYNAMICS MODEL FOR SPOT-WELDING ROBOT

This paper takes the latest developing SRD 165Kg spot-welding robot for example, as shown in Fig.2. In practical work of robots, the elastic deformation of each component has a certain influence to the welding precision. Because the upper arm is exposed under the worst working condition, the rigid-flexible coupling dynamics simulation is mainly completed by considering the robot upper arm as a flexible body.

Figure 2. SRD165A spot-welding robot

The mass distribution, moment of inertia and the geometric shape information of each component is very important. Under normal circumstances, these kinetic parameters may be identified through some other methods. As a result of the complexity of the robot, it is difficult to directly obtain the result of identification. This paper directly obtains geometric shape, material parameters and assembly relation information from three-dimensional CAD model in ADAMS, So as to the resulting kinetic parameters are needed [14]. On this basis, by adding appropriate constraint, force and kinematical relation, we can establish the virtual prototype of spot-welding robot.

A. *Establishment of rigid-body model*

Spot welding robot is mainly made up by the base, the waist joint, upper arm, forearm, wrist, balance cylinder and end effector etc, as shown in Fig.3. Welding operation of welding pliers is executed through the driving motor of each joint. Three-dimensional solid model of the robot is established by using SolidWorks software and imported into ADAMS. Then material properties are assigned to each component and motion pairs and drive are added to the model.

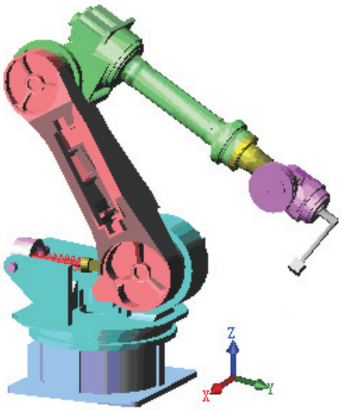


Figure 3. Multi-rigid-body model of Spot-welding robot

Where, adding a fixed pair between the base and earth and six revolute pairs on rotational joints. In addition, a revolute pair is added between balance cylinder rod and upper arm and a translational pair is added between cylinder block and cylinder rod. In order to prevent the generation of redundant constraints, an inline pair need to be built between cylinder block and lug. Redundant constraints are the so-called over-constraints. To the closed chain mechanism, we usually solve this problem using the lower pair.

In order to simulate the role of balance cylinder, a spring should be added between cylinder block and cylinder rod, and specify the spring stiffness, damping and preload value. To simulate the welding operations with load, a weight of 165kg is added to the tool end. In order to achieve the desired planning results, motion planning of each joint motor and the corresponding expression or data points of spline interpolation must be given. To illustrate the rigid-flexible coupling dynamic performance on the machine, the law of motion for each joint drive motor is respectively specified, so that to achieve six-axis machine.

B. *Establishment of flexible-body dynamics model*

In the finite element analysis software ANSYS, the upper arm of spot-welding robot can be transformed into flexible-body. Material properties, unit type, unit attributes and mesh parameter will be specified before meshing. According to constraint relation of upper arm in the ADAMS environment, three connection points need to be defined in the ANSYS. These points can help software establish the correct connection relation between flexible body and the other components [15]. The coordinates of external nodes under the global coordinate system are as shown in Table Ⅰ.

TABLE I. EXTERNAL CONNECTION NODES AND THEIR LOCATIONS UNDER GLOBAL COORDINATE SYSTEM (UNIT: mm)

Coordinate	**X**	**Y**	**Z**
10001	234.9	316.7	659.5
10002	235.5	117.3	578.9
10003	335.1	87.4	1656.2

After external connection points are defined, cyclic command need to be required in ANSYS. Through creating the rigid region on load bearing area using beam4 unit, we can use the interface of ADAMS and ANSYS to generate modal neutral file (.mnf file). In ADAMS/View, reading modal neutral file generated in ANSYS, the rigid upper arm of robot will be replaced with flexible-body, which generate rigid-flexible coupling dynamic model [16]. The upper arm flexible-body model generated in ANSYS is shown in Fig.4.

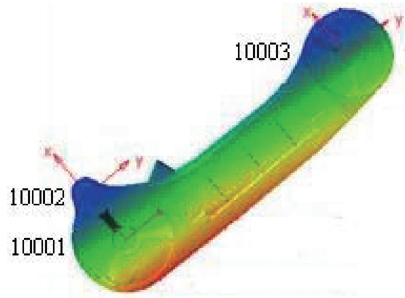


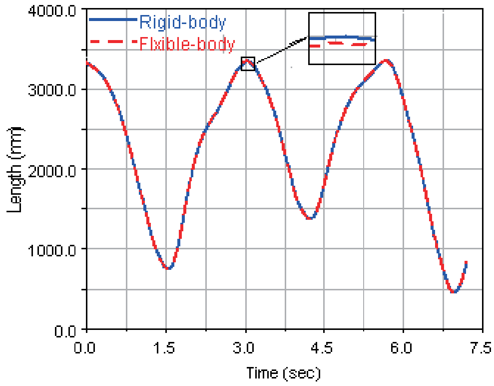
Figure 4. Flexible-body model of upper arm

IV. DYNAMICS SIMULATION ANALYSIS FOR SPOT-WELDING ROBOT

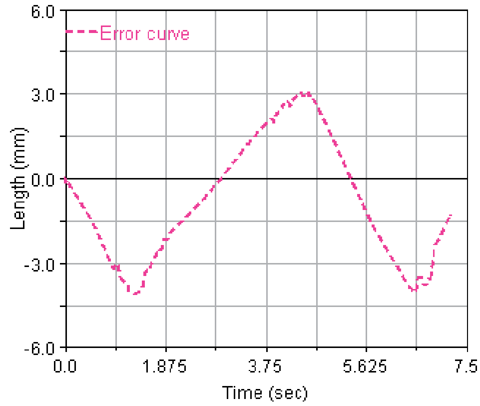
When spot-welding robot is at work, its configuration will constantly change to accommodate the location of different welding spot. Size and orientation of inertial loads acted on components are also continuously changed. These inertia loads include angular velocity, angular acceleration and linear acceleration of mass center. They are the main reasons to produce inertia force and moment of inertia. Because the stiffness matrix and mass distribution of the robot have difference under different configuration, the inertia loads what components can afford are also different. In rigid-flexible coupling dynamics simulation of spot-welding robot, we respectively select three typical configurations to study end measuring point's deformation in the vertical direction, such as the maximum height, maximum cantilever, and maximum anti-cantilever.

A. *Deformation of measuring point on end effector*

The end effector of robot will be deformed under external force. The size of its deformation has a decisive influence on the location accuracy for the spot welding robot. Through simulation analysis of full-rigid and rigid-flexible coupling model, we can get the displacement curve and deformation of measuring point along the vertical direction, as shown in Fig.5.



(a) Displacement curve



(b) Error curve

Figure 5. Displacement and deformation of measuring point along along the vertical direction

As can be seen from the Fig.5 (a), simulation curves of the two models have certain error under the same motion law and load step. The variation of displacement is caused by the flexible body of upper arm, and corresponding to different configurations, the value is plus or minus. Fig.5 (b) is the error curve of end measuring point under the two models. With the two ps combination, we can get the following results:

- In the time 1.5s, the robot is at the maximum cantilever configuration, and the biggest deformation amplitude caused by flexible body is 4.11mm in the vertical direction.
- In the time 3.0s, the robot is at the maximum height configuration, and the biggest deformation amplitude caused by flexible body is 0.28mm in the vertical direction.
- In the time 4.2s, the robot is at the maximum anti-cantilever configuration, and at that moment the biggest deformation amplitude caused by flexible body is 3.06mm in the vertical direction.

The followings are three typical configuration deformation amplitude of end measuring point in the vertical direction, as shown in table Ⅱ.

TABLE II. DEFORMATION OF MEASURING POINT ALONG THE VERTICAL DIRECTION UNDER THREE TYPICAL CONFIGURATION (UNIT: mm)

Deformation	**Maximum height**	**Maximum cantilever**	**Maximum anti-cantilever**
Rigid-body	3338.13	745.12	1372.54
Flexible-body	3337.85	749.23	1369.86
Deformation	0.28	4.11	2.70

Simulation found that the deformation of end measuring point is larger in the vertical direction corresponds to maximum cantilever configuration. This was mainly caused by poor stiffness and harsh working conditions of this kind of configuration. In order to improve its stiffness, we can change upper arm design by adding rib plate. However, in its practical work, we'd better avoid this extreme configuration and try to make it work in the middle section of the joint space. In addition, to a particular welding operation, we should ensure that the inertia loads generated in motion are as small as possible. This requires us to make a reasonable trajectory plan to ensure the positioning accuracy of the end welding pliers and improve the quality of welding.

B. Stress on upper arm of robot

Through rigid-flexible coupling dynamics simulation with flexible-body model of upper arm, we get maximum stress of upper arm in a work period. Configuration of the robot and the corresponding curves of the maximum stress point are shown in Fig.6 and Fig.7.

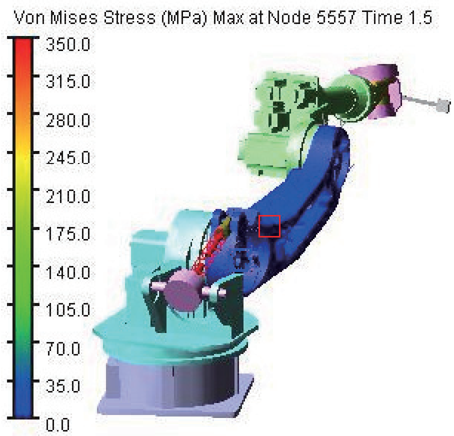


Figure 6. Maximum stress position and value

As shown in Fig.6, we found that the maximum stress occurred on the root of upper arm, corresponding to the maximum cantilever configuration and the time is 1.5s. The maximum Von Mises Stress is 316Mpa, which is less than the yield limit 620Mpa of alloy steel, so the upper arm is secure.

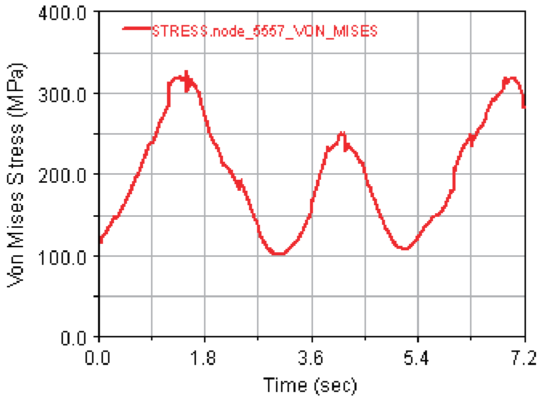


Figure 7. Stress curve of node 5557

Fig.7 shows the stress curve of node 5557, which is under the greatest stress. In the time 3.0s, the maximum stress is 100MPa, corresponding to the maximum height configuration. From the picture, we can also find that the stress curve has another peak in the 4.2s, and at that time the robot is under the maximum anti-cantilever configuration. Take these two configurations as extremity, and so on, the whole curve shows periodic variation. The Maximum Von Mises Stress of node 5557 under three typical configurations is as shown in Table III.

TABLE III. TABLE. III MAXIMUM VON MISES STRESS OF NODE 5557 UNDER THREE TYPICAL CONFIGURATIONS (UNIT: MPa)

Stress	**Maximum height**	**Maximum cantilever**	**Maximum anti-cantilever**
Von Mises	100	316	246

Simulation found that the current design intensity is adequate. But we should observe that the maximum stress position occurred at the same position with the different configuration and load step. This indicates that fatigue failure may occur in the region. The constant accumulation of stress energy is very unfavorable, so the further testing and analysis of fatigue must be conducted. The present results can be considered for further analysis.

V. CONCLUSION

This paper completed motion simulation and stress analysis of rigid-flexible coupling dynamics model of spot-welding robot by using ADAMS and ANSYS co-simulation technology. Through combining their advantages and overcoming their limitations alone, It has greatly improved the analysis efficiency and simulation accuracy. The conclusion is as follows:

1) Through the rigid-flexible coupling dynamics simulation, we have got the displacement curve and deformation of measuring point in the vertical direction. The maximum deformation position of robot is in Maximum cantilever configuration, the value of deformation is 4.11 mm.

2) During a period of motion, we have obtained the position and the curve of maximum stress point. Results show that the maximum Von Mises stress is 316Mpa, which is less than the material yield strength

3) The analysis method of rigid-flexible coupling dynamic simulation is intuitional and accurate, and can increase the accuracy of dynamic response analysis of parts under the dynamic loads. It is very useful to accurately simulate the actual work of point-welding robot.

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