

THE DYNAMICS STABILITY JUDGING METHOD FOR A GANTRY-TYPE WELDING ROBOT

Zheng Mingliang ^{1,2}

Received on April 22, 2024

Presented by Ch. Roumenin, Member of BAS, on July 30, 2024

Abstract

In order to improve the dynamic performance of gantry-type welding robot, this paper introduces the structural dynamics model and Lyapunov stability criterion of the gantry-type welding robot frame with nine degrees of freedom. The dynamic equations of the welding robot satisfy the Euler–Lagrange form, and the calculation index of welding robot Lyapunov stability is judged by matrix eigenvalues. Combining with the specific design parameters of an industrial welding robot, the motion stability of the gantry-type welding robot frame and the displacement response of the welding torch are analyzed. The influence of the change of the frame design structure on the stability of the welding torch for end effector of welding robot is discussed, furthermore, the improvement direction of vibration damping and anti-interference of welding robot system is pointed out. Finally, the dynamics simulation of the optimized gantry-type welding robot end effector is carried out by using ADAMS software, and the torque variation curve of the end effector is obtained, which provides a strong basis for the selection of motor models and the design of control system.

Key words: gantry-type welding robot, frame, Lyapunov, stability

Introduction. Gantry-type welding robot is a kind of rectangular coordinate robot, which has the characteristics of large stroke, large load and good support rigidity [1], so it has important applications in industrial production. At present,

This research received funding by Qing Lan Project of Universities in Jiangsu Province (2022–29).

<https://doi.org/10.7546/CRABS.2024.09.12>

the scholars' research mainly focus on the kinematics and static structure optimization [2–10], but the research on its dynamic characteristics is still lacking. In fact, due to various interference factors, such as impact, friction, wind, centre of gravity offset and counterweight imbalance, the gantry frame will have deformation and vibration during high-speed operation. If the gantry frame vibrates violently, not only the noise is loud, but also the overall structure may be damaged. Therefore, in order to make the welding robot work with higher accuracy and stability, how to avoid the mechanism vibration from the design point of view is a basic topic.

The research on the stability of robot motion has always been an important part of robotics. The main criteria methods for stability are [11–14]: momentum method; ZMP method; stability margin method of force-angle; stability margin method of energy; Poincare–Lyapunov theory. However, through literature review, it is found that the research on dynamic stability of welding robot is not sufficient, which is mainly reflected by the lack of effective stability criteria.

The novel contribution of this paper: (1) Considering the nonlinearity of the dynamic equations of a welding robot, the Lyapunov stability analysis method is applied to the stability analysis of a gantry-type welding robot under impact excitation. This method overcomes the limitations of small displacement motion. (2) Based on simulation results, an optimization scheme for the gantry structure of welding robot was proposed, which completely solved the dynamic instability problem of large vibration amplitude and slow vibration attenuation.

Materials and methods. This paper deals with the phenomenon that the gantry frame crossbeam of an industrial welding robot is greatly deformed under the impact of motor braking, resulting in the vibration of the robot body and unstable welding quality. In order to accurately evaluate the motion stability and immunity of the welding robot, the dynamic model of the gantry frame is established according to the Euler–Lagrange equations. Further, using the Lyapunov stability theory, the stability of the system is quantitatively judged, the reason for the vibration instability of the system is found, and the improvement measures are proposed.

Results and discussion. Research has shown that the quantitative calculation of the dynamic stability of the gantry-type welding robot provides a basis for structural optimization.

Dynamic model of gantry-type welding robot. The three-dimensional solid structure of a gantry-type industrial arc welding robot studied in this paper is shown in Fig. 1(a). The gantry is the main load-bearing structure of welding robot, which is mainly composed of cross beam, column, bases, and ground rail walking system. These structures are connected by bolts, guide rails, brackets, and bearings to form the overall gantry, which can achieve three-axis driving of the X-axis, Y-axis, and Z-axis. The main structural components of the welding robot body are installed on the cross beam of the gantry frame. The cross beam

is fixed to the two end columns through group bolt connections, and the columns are also fixed to the base of the gantry frame through bolt connections. The bolts are symmetrically arranged, which can ensure that the entire gantry frame is uniformly stressed and has high stability. The column is connected downwards to the ground rail walking mechanism, and the ground rail walking system adopts a steel rail walking mechanism instead of a traditional slider walking mechanism. The longitudinal movement of the gantry welding robot is generally driven by two or four motors, with one or two motors at each end of the gantry frame. After being decelerated by an AC motor through a gearbox, the gantry frame is then driven to move longitudinally on the guide rail. The base of the welding robot studied in this article is fixed on the lifting mechanism of the gantry cross beam. The welding robot body has six rotating joints, and the gantry has three translational joints, forming a total of nine joints gantry welding robot. The nine-degree-of-freedom joints operation mode is shown in Fig. 1(b).

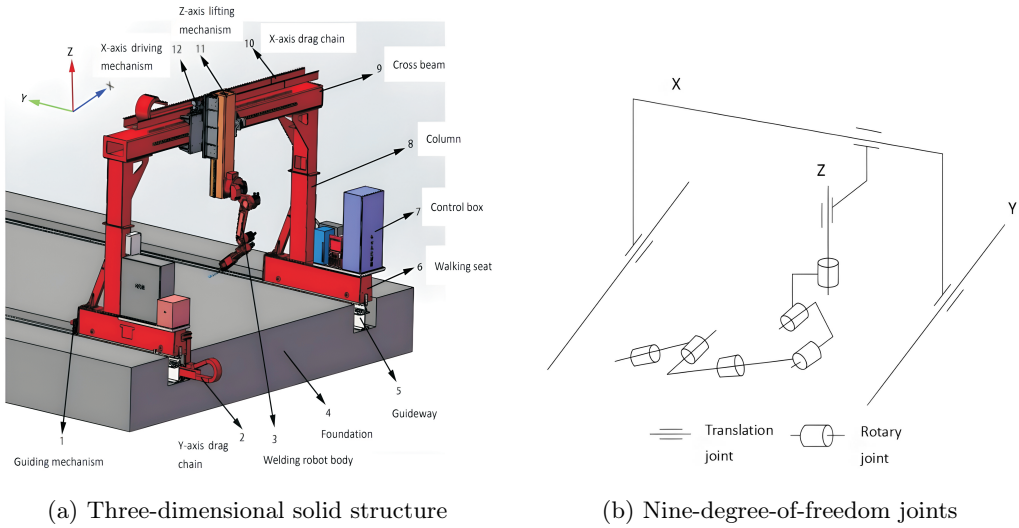


Fig. 1. Schematic diagram of gantry-type welding robot joints

Because the standard industrial arc welding robot body with six-degrees of freedom has been mature and industrialized both in design and control, its dynamic performance has been relatively perfect. At the same time, the robot workstation can realize functional decoupling of the robot body, gantry motion frame and positioner. Therefore, it can be considered that the structural dynamic characteristics of the gantry frame directly determine the welding accuracy

of the entire robot. In order to simplify the mathematical model, we only conduct dynamic analysis on the gantry frame structure of the welding robot with three-degree-of-freedom. The kinetic energy of the system is expressed as:

$$(1) \quad T = \frac{1}{2}(M_x \dot{x}^2 + M_y \dot{y}^2 + M_z \dot{z}^2) + \frac{1}{2}mv_m^2$$

$$v_m = \dot{x}^2 + \dot{y}^2 + \dot{z}^2.$$

Here, M_x , M_y , M_z , respectively, represent the equivalent mass components of the motors, the trusses and their actuators in the welding robot system in the x , y , z directions, m is the load mass, and v_m is the speed of load movement.

According to the Lagrange equations [15] of the unconstrained mechanical multi-body system, the dynamic form of the gantry frame is:

$$(2) \quad \frac{d}{dt} \left(\frac{\partial T}{\partial \dot{x}} \right) - \frac{\partial T}{\partial x} = f_x - D_x \dot{x}$$

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{y}} \right) - \frac{\partial T}{\partial y} = f_y - D_y \dot{y}$$

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{z}} \right) - \frac{\partial T}{\partial z} = f_z - D_z \dot{z}$$

Furthermore, its matrix form is:

$$(3) \quad M(\mathbf{q})\ddot{\mathbf{q}} + D\dot{\mathbf{q}} + C(\mathbf{q}, \dot{\mathbf{q}})\mathbf{q} + G(\mathbf{q}) = \tau.$$

Here, $\mathbf{q} = (x, y, z)^T$ is the generalized coordinate vector, $M(\mathbf{q})$ is the inertia mass matrix of the system, $C(\mathbf{q}, \dot{\mathbf{q}})$ is the centripetal force and Coriolis force matrix related to the position and velocity, D is the damping matrix of the system, $G(\mathbf{q})$ is the gravity action matrix of the system, and $\tau = [f_x, f_y, f_z]^T$ is the input torque control quantity.

For the standard industrial arc welding robot body with six rotational degrees of freedom, the unit vectors are $\mathbf{e}_1 = (1, 0, 0)^T$, $\mathbf{e}_2 = (0, 1, 0)^T$, $\mathbf{e}_3 = (0, 0, 1)^T$, in reference [19], the angular velocity ${}^i\boldsymbol{\omega}_i$, angular acceleration ${}^i\dot{\boldsymbol{\omega}}_i$, origin acceleration ${}^i\mathbf{a}_i$, centre of mass acceleration ${}^i\mathbf{a}_{Ci}$, inertial force ${}^i\mathbf{f}_{Ci}$, inertial torque ${}^i\mathbf{n}_{Ci}$, and

driving torque $\mathbf{\Gamma}_i$ of connecting rod i are:

$$\begin{aligned}
\boldsymbol{\omega}_i &= {}^i_{i-1}\mathbf{R}^{i-1}\boldsymbol{\omega}_{i-1} + \dot{\theta}_i\mathbf{e}_3, \\
{}^i\dot{\boldsymbol{\omega}}_i &= {}^i_{i-1}\mathbf{R}^{i-1}\dot{\boldsymbol{\omega}}_{i-1} + {}^i_{i-1}\mathbf{R}^{i-1}\boldsymbol{\omega}_{i-1} \times \dot{\theta}_i\mathbf{e}_3 + \ddot{\theta}_i\mathbf{e}_3, \\
{}^i\mathbf{a}_i &= {}^i_{i-1}\mathbf{R}({}^{i-1}\mathbf{a}_{i-1} + {}^{i-1}\dot{\boldsymbol{\omega}}_{i-1} \times {}^{i-1}\mathbf{p}_i + \boldsymbol{\omega}_{i-1} \times ({}^{i-1}\boldsymbol{\omega}_{i-1} \times {}^{i-1}\mathbf{p}_i)), \\
{}^i\mathbf{a}_{Ci} &= {}^i\mathbf{a}_i + {}^i\dot{\boldsymbol{\omega}}_i \times {}^i\mathbf{p}_{Ci} + {}^i\dot{\boldsymbol{\omega}}_i \times ({}^i\boldsymbol{\omega}_i \times {}^i\mathbf{p}_{Ci}), \\
(4) \quad {}^i\mathbf{f}_{Ci} &= m_i {}^i\mathbf{a}_{Ci}, \\
{}^i\mathbf{n}_{Ci} &= {}^i\mathbf{I}_{Ci} {}^i\dot{\boldsymbol{\omega}}_i + {}^i\dot{\boldsymbol{\omega}}_i \times ({}^i\mathbf{I}_{Ci} {}^i\boldsymbol{\omega}_i), \\
\mathbf{\Gamma}_i &= {}^i\mathbf{n}_i\mathbf{e}_3, \\
{}^i\mathbf{f}_i &= {}^i_{i+1}\mathbf{R}^{i+1}\mathbf{f}_{i+1} + {}^i\mathbf{f}_{Ci}, \\
{}^i\mathbf{n}_i &= {}^i_{i+1}\mathbf{R}^{i+1}\mathbf{n}_{i+1} + {}^i\mathbf{n}_{Ci} + {}^i\mathbf{p}_{Ci} \times {}^i\mathbf{f}_{Ci} + {}^i\mathbf{p}_{i+1} \times {}^i_{i+1}\mathbf{R}^{i+1}\mathbf{f}_{i+1}.
\end{aligned}$$

Here, ${}^i_{i-1}\mathbf{R}$ is the attitude transformation matrix, ${}^i\mathbf{p}_{Ci}$ are the coordinates of the centre of mass, ${}^{i-1}\mathbf{p}_i$ are the origin coordinates, ${}^i\mathbf{I}_{Ci}$ is the inertia matrix relative to centre of mass, θ_i is the rotation angle from rod $i-1$ axis to rod i axis.

Stability criterion. The essence of the stability problem is to investigate whether the disturbed motion caused by the initial state disturbance of the system can approach or return to the original equilibrium state [16]. For a general nonlinear system:

$$(5) \quad \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t).$$

Importantly, $\mathbf{f}(\mathbf{x}_e, t) = 0$ represents the state of constant motion or equilibrium when the system is not disturbed.

Now, we introduce the definition of Lyapunov stability [16], that is: for any $\varepsilon > 0$, if there is a $\delta(\varepsilon, t_0) > 0$, when $\|\mathbf{x}_0 - \mathbf{x}_e\| \leq \delta(\varepsilon, t_0)$, $t \geq t_0$, there is $|\Phi(t, x_0, t_0) - \mathbf{x}_e| \leq \varepsilon$, so the equilibrium state $\mathbf{x}_e$ is called stable. And if the δ is independent of the initial time, so the equilibrium state $\mathbf{x}_e$ is uniformly stable. And if $\lim_{t \rightarrow \infty} \|\Phi(t, \mathbf{x}_0, t_0) - \mathbf{x}_e\| = 0$, so the equilibrium state $\mathbf{x}_e$ is asymptotically stable.

Lyapunov pointed out that if the system has a scalar energy function $V(\mathbf{x}, t)$ (it is also called Lyapunov function), and $\dot{V}(\mathbf{x}, t)$ is positive definite and $\dot{V}(\mathbf{x}, t)$ is negative definite or negative semidefinite, then the system is stable.

For nonlinear systems, there is no general method for constructing Lyapunov function, so it is difficult for Lyapunov decision method to judge whether the solution $\mathbf{x}_e$ of the system is stable no matter through the energy function and the solution of the state equation. Therefore, we expand the nonlinear system at the

equilibrium solution $\mathbf{x}_e$, so we can rewrite equation (5) as:

$$(6) \quad \dot{\mathbf{x}} = A\mathbf{x} + \mathbf{g}(\mathbf{x}, t).$$

Here, A is the Jacobi matrix of $\mathbf{f}(\mathbf{x})$ at the equilibrium solution $\mathbf{x}_e$, $\mathbf{g}(\mathbf{x}, t)$ is the simplified higher-order term of the system.

Especially, we write the dynamic equation (3) of the gantry-type welding robot into the form of equation (6) by augmenting vector $\mathbf{X} = [\dot{x}, \dot{y}, \dot{z}, x, y, z]^T$. According to Lyapunov's first approximation theory [16], that is: if all eigenvalues of Jacobi matrix A have negative real parts, so the equilibrium state of the system is asymptotically stable. Nevertheless, if the matrix A has multiple eigenvalues, λ_j is a multiple eigenvalue of k -order, when the real part of λ_j is 0 (it is a pure imaginary root), and the order of its corresponding Jordan block J_k is 1, and the higher-order term also tends to converge, so the system is still stable. For other types of cases, the equilibrium state of the system is unstable. If the dynamic characteristics of the gantry-type welding robot frame are unstable when moving, the lifting of the mechanism will cause the axial torsion of the system to produce vibration, and the mechanism will produce abnormal noise.

In addition, different from Lyapunov's decision method, it should be pointed out that if equation (3) can be decoupled through coordinate transformation (multiplied by $M^{-1}(\mathbf{q})$), the stability of the system can also be judged according to the motion stability problem of the particular solution of forced vibration for a single degree of freedom system is equivalent to the stability problem of the free vibration for a single degree of freedom system.

Application example. The specific parameters of a gantry-type industrial welding robot frame [17, 18] are as follows: the materials are ordinary carbon steel, the transverse gauge (X-axis) is 3000 mm, the travel of X-axis is 2500 mm, the travel of Y-axis is 3500 mm, the working range is 2500–3500 mm, and the travel of Z-axis by the vertical lifting mechanism is 650 mm. The crane travelling (Y-axis) adopts bilateral servo motor, and the guide rail is configured as a precision linear guide rail, as well as a diagonal rack and a ball screw brake. The crossbeam load is a standard industrial robot with six axis, each joint of which is a rotation axis. Respectively, the mass and centre of gravity position of each robot link of the welding robot with six axis are

$$(m_1, r_{x1}, r_{y1}, r_{z1}) = (138.79, 0.0647, 0.3765, 0.0756),$$

$$(m_2, r_{x2}, r_{y2}, r_{z2}) = (94.72, 0.1867, 0.7973, 0.2344),$$

$$(m_3, r_{x3}, r_{y3}, r_{z3}) = (32.61, 0.2045, 1.1808, 0.0703),$$

$$(m_4, r_{x4}, r_{y4}, r_{z4}) = (27.95, 0.6907, 1.2042, 0.0385),$$

$$(m_5, r_{x5}, r_{y5}, r_{z5}) = (13.48, 0.8763, 1.2164, 0.0264),$$

$$(m_6, r_{x6}, r_{y6}, r_{z6}) = (0.33, 0.9750, 1.2259, 0.0291).$$

The principal moment of inertia of each connecting rod of a six rotational joint robot is

$$\begin{aligned}
 I_1 &= \begin{bmatrix} 5.2365 & 0 & 0 \\ 0 & 5.0411 & 0 \\ 0 & 0 & 1.7314 \end{bmatrix}, & I_2 &= \begin{bmatrix} 4.7553 & 0 & 0 \\ 0 & 4.7102 & 0 \\ 0 & 0 & 0.5016 \end{bmatrix}, \\
 I_3 &= \begin{bmatrix} 1.0518 & 0 & 0 \\ 0 & 0.9744 & 0 \\ 0 & 0 & 0.1741 \end{bmatrix}, & I_4 &= \begin{bmatrix} 0.2885 & 0 & 0 \\ 0 & 0.2880 & 0 \\ 0 & 0 & 6.1629 \end{bmatrix}, \\
 I_5 &= \begin{bmatrix} 9.3291 & 0 & 0 \\ 0 & 7.0137 & 0 \\ 0 & 0 & 4.8810 \end{bmatrix}, & I_6 &= \begin{bmatrix} 2.1742 & 0 & 0 \\ 0 & 1.1260 & 0 \\ 0 & 0 & 1.1260 \end{bmatrix}.
 \end{aligned}$$

The damping ratio of steel structure is 0.05. This paper considers the dynamic response and stability of the gantry frame when the motor is braked rapidly. The acceleration of motor during fast braking is 2 m/s².

According to dynamic equation (2) of the system and the linearized equation, we can get the mass matrix M of the system and the eigenvalues distribution of the linearized characteristic matrix A as follows:

$$(7) \quad \text{diag}(-0.2389 - 0.8714j, -0.2389 + 0.8714j, 0.0415 - 1.0451j, \\ 0.415 + 1.0451j, -0.0143 - 0.0180j, -0.0143 + 0.0180j).$$

So according to the Lyapunov stability judgment method, we can conclude that the system is unstable.

In order to improve the stability of the gantry frame, a connecting frame is added at the non-feed inlet side of the upright column. The single side crossbeam was changed to the double side crossbeam, the counterweight was cancelled, and the sliding box was added. The structure of connecting frame and crossbeam are shown in Fig. 2.

Therefore, we changed its mass matrix M . The eigenvalues distribution of the linearized characteristic matrix A for the improved system was:

$$(8) \quad \text{diag}(-0.6776 - 1.5588j, -0.6776 + 1.5588j, -0.0296 - 1.8718j, \\ -0.0296 + 1.8718j, -0.0179 - 0.0337j, -0.0179 + 0.0337j).$$

We can see that the real parts of eigenvalues are all negative real numbers, so the improved system is stable.

Next, we use the ANSYS Workbench software to simulate the dynamic characteristics of the pre-optimized and post optimized gantry-type welding robot frames during the braking process separately. The parameters of the simulation:

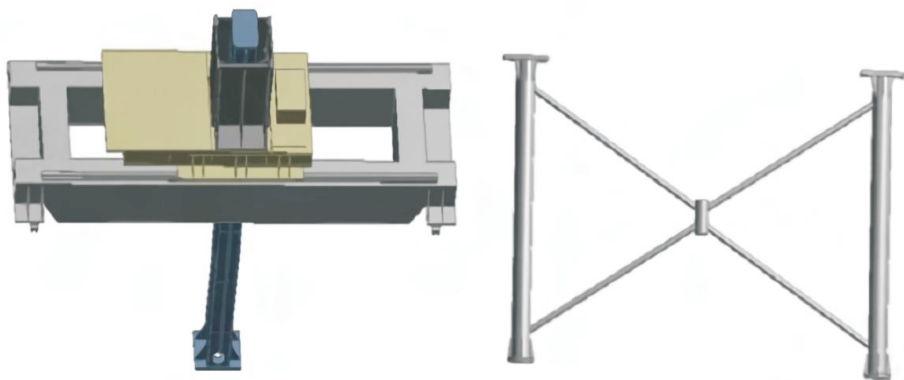
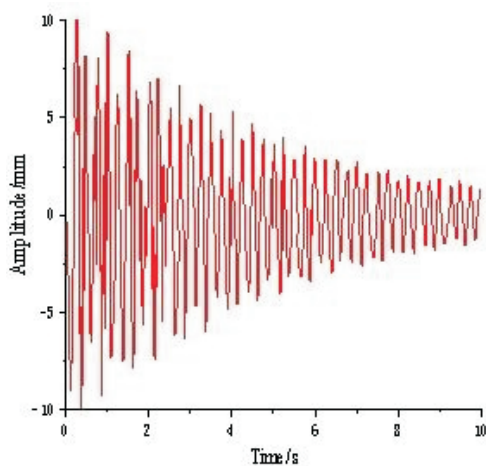
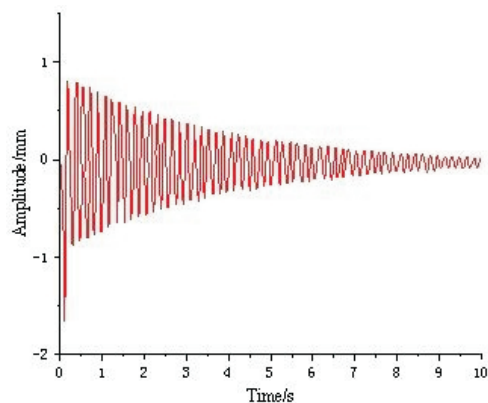


Fig. 2. Improved crossbeam and connecting frame

The tetrahedrons mesh division size is set to 10 mm, with a total of 309531 nodes and 89196 units. Material selection Q235. Applying cylindrical support constraints to columns. The damping ratio of steel structure is 0.05. The acceleration of motor during fast braking is 2 m/s^2 along the positive of X-axis. Applying an external excitation force of 150 N on the Z-axis in the middle part of the gantry cross beam. Setting the integration time step to 0.01 s. Invoking the Mode Super position method of the Harmonic Response module in ANSYS Workbench, the result is shown in Fig. 3. It can be seen in Fig. 3(a) that for pre-optimized gantry-type welding robot frame, the maximum amplitude in the positive X direction is 10.26 mm, and the maximum amplitude in the negative



(a) Pre-optimized



(b) Post optimized

Fig. 3. Amplitude responses of the pre-optimized and post optimized robot welding guns in X direction

X direction is 10.19 mm. Now, we can judge that the welding gun of the robot vibrates seriously, which causes the robot to be unable to work normally, so the system is unstable. It can be seen in Fig. 3(b) that for post optimized gantry-type welding robot frame, the maximum amplitude in the positive X direction is 0.89 mm, which is decreased by 91.3% after the optimization. The maximum amplitude in the negative X direction is -1.68 mm, which is decreased by 83.4% after the optimization. So the welding accuracy has been greatly improved. Importantly, the attenuation rate of welding gun vibration is significantly accelerated, so the improved system is stable.

The dynamics simulation of optimized robot. The dynamics of robot is related to acceleration, load, mass, and inertia, and its characteristics include the coupling effect of each joint, the nonlinear effects of Coriolis force and centrifugal force. The main task of dynamic analysis is to analyze the relationship between driving torque and joint motion. The results of dynamic analysis are helpful for driver selection and are a prerequisite for achieving high-precision real-time control of robot. Similarly, based on dynamic analysis, structural parameters can be optimized to obtain the optimal structural solution. Importing the Parasolid format of the 3D virtual prototype of the gantry welding robot into ADAMS software, then simulating the overall dynamics of the gantry welding robot by using ADAMS software. The setting steps are as follows: (1) The model units adopt the MMKS metric system. (2) The gravitational acceleration is 10 g/m^2 . (3) The material of parts is the gantry Q235 and the rest are all 45 steel. (4) The constraint forms are adding the fixed pairs to the guide rail, mobile pairs between the walking platform and the guide rail, mobile pairs between the gantry cross beam and the column, and rotating pairs between the joints of the six-axis welding robotic arm. (5) The friction forces of joints are: static friction coefficient 0.5, and dynamic friction coefficient 0.25. (6) The load is a force of 70 N added along the negative Y-axis direction. (7) The motor drive function is applying a velocity driving function in the Z-axis direction

$$\begin{aligned} \text{velo}(\text{time}) = & \text{STEP}(\text{time}, 0, 0, 1, 20) + \text{STEP}(\text{time}, 4, 0, 5, -20) \\ & + \text{STEP}(\text{time}, 6, 0, 7, -20) + \text{STEP}(\text{time}, 9, 0, 10, 20). \end{aligned}$$

The simulation time is 5 seconds, and the time step is 0.01 second. The curve of the torque acting on the end effector over time is shown in Fig. 4.

In Fig. 4 it can be seen that before and after optimizing the gantry, the overall trend of torque change of the robot's end effector is basically the same, and there is no sudden change in the torque curve of optimized gantry welding robot, so the robot has good dynamic performance and reasonable structural design. Comparing with the pre-optimized gantry, the torque change of the end effector of the optimized robot is smoother and the sharp peaks are not prominent, meanwhile, the maximum starting torque is approximately 10 000 Nm and the start-up time is approximately 0.6 s for optimized gantry welding robot, but the

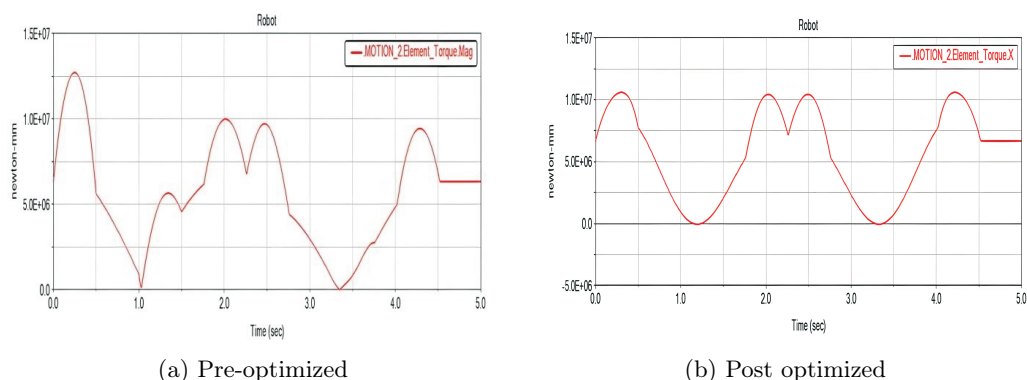


Fig. 4. Torque acting on the end effector of welding robot for the pre-optimized and post optimized gantry frame

maximum starting torque is approximately 12 600 Nm and the start-up time is approximately 1.0 s for pre-optimized gantry welding robot, so improving the gantry is an effective optimization approach to enhance the dynamic performance of robot.

Conclusions. By applying the acceleration impact load of motor braking, the dynamic response of the gantry frame structure of the gantry-type welding robot was analyzed. According to the 3×3 dynamic mass matrix and the eigenvalues distribution of the 6×6 augmented Jacobian matrix, it is found that the connecting part is the weak link of the gantry frame, and the counterweight structure would aggravate the vibration of the robot manipulator arm. Therefore the original system did not meet the Lyapunov stability criterion.

The motion stability of the gantry frame is improved. The connecting frame is added to the non-feed inlet side of the upright column, the single side cross beam is changed to the double side crossbeam, the counterweight is cancelled, and the sliding box is added. The eigenvalues of the Jacobian matrix of the improved model are solved. The results show that the real parts of the eigenvalues are all negative, the maximum amplitude of the robot welding gun vibration in the positive X direction is reduced by 91.3%, the maximum amplitude of the robot welding gun vibration in the negative X direction is reduced by 83.4%, and the attenuation speed of the vibration is greatly increased, so the improved gantry-type robot welding meets the requirements of the actual welding stability.

Under the ADAMS simulation environment, through simulation comparison of the driving torque changes of the robot's end effector before and after optimizing the gantry structure, it was found that the stability of the gantry is directly related to the maximum peak, smoothness, and start-up response time of the driving torque of the end effector. The optimized gantry welding robot did not experience significant impacts during operation, and the end effector operated relatively smoothly.

REFERENCES

- [1] LIU D. (2022) Mechanical Structure Optimization Design of Large Gantry Frame Welding Robot, PhD Thesis, Xiamen, Xiamen University of Technology, 7–13.
- [2] JIANG Y., Q. HAN, Z. DAI et al. (2022) Structural design and kinematic analysis of a welding robot for liquefied natural gas membrane tank automatic welding, *Int. J. Adv. Manufact. Technol.*, **122**, 461–474.
- [3] CHANGCHUN S., L. SHUIMING, H. YING (2019) Coordinated motion analysis and simulation of arc welding robot and positioner, *Journal of Physics: Conference Series*, **1168**(2), 22–32.
- [4] LI C., X. G. MA, G. B. ZHAO (2103) Rigidity-Flexibility Coupling Motion Simulation of the Open Arc Welding Robot in ADAMS, *Adv. Mater. Res.*, **2385**, 1675–1678.
- [5] CHEN S. L. (2014) Design of Simulation for Arc Welding Robot Based on OpenGL, *Appl. Mechanics Mater.*, **3365**, 12–22.
- [6] LIU Z., W. BU, J. TAN (2010) Motion navigation for arc welding robots based on feature mapping in a simulation environment, *Robotics and Computer-Integrated Manufacturing*, **26**(2), 137–144.
- [7] SOBASZEK L., A. ŚWIĆ (2021) Scheduling the Process of Robot Welding of Thin-Walled Steel Sheet Structures under Constraint, *Appl. Sci.*, **11**(12), 5683.
- [8] SATAKE Y., A. TAKANISHI, H. ISHII (2020) Novel Growing Robot with Inflatable Structure and Heat Welding Rotation Mechanism, *IEEE/ASME Transactions on Mechatronics*, **25**, 1869–1877.
- [9] KU N., J. CHA, K. LEE et al. (2020) Development of a mobile welding robot for double-hull structures in shipbuilding, *Journal of Marine Science and Technology*, **15**(4), 374–385.
- [10] PORUBA Z., J. PODEŠVA, O. FRANTIŠEK et al. (2016) Strength analysis and optimization of welding robot mechanism in emergency stop state, *Perspectives in Science*, **7**, 347–352.
- [11] CVITANIC T., S. N. MELKOTE (2022) A new method for closed-loop stability prediction in industrial robots, *Robotics and Computer-Integrated Manufacturing*, **73**(2), 102218.
- [12] XIE Z. D., B. LI, C. CHEN (2022) Stability Analysis of Lower Limb Exoskeleton Robot Based on ZMP Theory, *Mechanical Engineering*, **5**, 1–5.
- [13] NGUYEN T., H. Q. LE, Y. M. JEONG, S. Y. YANG (2014) A Study of Stability for Field Robot Using Energy Stability Method, *Journal of Drive and Control*, **11**(3), 22–30.
- [14] LIU Z. M., W. J. QIAN, Z. L. XIA (2004) Analysis of Dynamic Stability of Underwater Vehicle Navigating in Planar and Straight Course, *Ship Engineering*, **26**, 54–56.
- [15] MEI F. X. (1991) Lagrangianization of dynamic equations in *Advanced Analytical Mechanics* (Ed. Liu Y. G.), Beijing, Beijing University of Technology Press, 35–42.
- [16] NI H. (2006) The Extension of the Theories about Liapunov's Concerning the Stability of Zero Solutions of Nonlinear Differential Equations and Its Applications, PhD Thesis, Fuzhou, Fuzhou University, 50–61.
- [17] CAI Y. Q., D. S. ZHU (2017) Dynamic Characteristics Optimization of Braking Process of Gantry-type Welding Robot, *Journal of North China University of Science and Technology (Natural Science Edition)*, **39**, 53–60.

- [18] LIU C. (2018) Research on Weld Tracking System of Gantry Welding Robot, PhD Thesis, Nanchang, Nanchang University, 65–72.
- [19] PANG Y. J. (2021) Design and Analysis of Wind Turbine Blade Grinding Robot, PhD Thesis, Shijiazhuang, Yanshan University, 52–60.

¹*Mechanical and Electrical Engineering, Huainan Normal University,
Huainan 232038, China*

e-mail: liangmingzheng@hnnu.edu.cn, <https://orcid.org/0000-0001-5681-0051>

²*Human-computer Collaborative Robot Joint Laboratory of Anhui Province,
Huainan 232038, China*