

Article

Adaptive End-Effector Buffeting Sliding Mode Control for Heavy-Duty Robots with Long Arms

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Abstract: This study aims to resolve the problems of low precision, poor flexibility and unstable operation in the control performance of loading robots with long telescopic booms and heavy loads. Firstly, the kinematics and dynamics of long-arm heavy-duty robots are analyzed, and the dynamics model of a long-arm heavy-duty robot is established using the Lagrange method. A new power-hybrid sliding-mode approach law is proposed, and a hybrid force/position control strategy is used to control long-arm heavy-duty robots. The position control of long-arm heavy-duty robots uses a new sliding-mode adaptive control to improve the position accuracy of important joints, and PD control is used to force control the other joints. The two-stage telescopic arm is flexible and the long-arm heavy-load robot is simulated. The simulation results show that the long-arm heavy-load robot obtained using the improved sliding-mode adaptive control algorithm has good track-tracking and jitter-suppression effects. The new power-hybrid sliding-mode controller designed in this paper reduces the jitter amplitude of the end-effector of long-arm heavy-duty robots by 28.75%, 10.92% and 16.22%, respectively, compared with the existing new approach law sliding-mode controller. The simulation results show that the proposed power-hybrid reaching law sliding-mode controller can effectively reduce the amplitude difference of the end-effector. Finally, the force/position control strategy is combined with force-based impedance control, and the design process of impedance controller parameters is introduced, which provides a reference for the trajectory-tracking and vibration-suppression of end-effectors of long-arm heavy-duty robots.

Keywords: adaptive sliding-mode control; end-effector chattering; long-arm heavy-duty robot; impedance control

MSC: 37M05



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1. Introduction

With the rapid development of industrial robot research [1], palletizing vehicle robots have gained unprecedented favor in the field of intelligent equipment at the beginning of logistics. As a convenient handling tool, the palletizing machine robot has saved transportation costs and improved handling efficiency for many industries. It plays an important role in industry. Long-arm heavy-duty robots are a kind of palletizing robot with a high degree of automation and wide range of application. However, the end-effector of the long-arm heavy-duty robot will be affected by the characteristics of a long telescopic arm and heavy load, which will lead to the deformation and chattering of the telescopic arm and cause great damage to the life of the long-arm heavy-duty robot. It is difficult to realize the accurate position and trajectory-tracking control of the long-arm heavy-duty robot system.

Therefore, it is of great engineering significance to improve the dynamic performance of the telescopic boom with stable motion and high trajectory-tracking accuracy, and to reduce the end-effector jitter of the long-arm heavy-duty robot.

Sliding mode control, because of its low dependence on the system model, displays invariance when the system is subjected to external interference and parameter perturbation. It is a robust and strong anti-interference nonlinear control method, and has been widely used in the controller design of trajectory-tracking. Wang Xiaojun proposed a non-singular fast terminal sliding-mode control method to reduce the control performance of flexible manipulators due to the uncertain dynamic parameters and other factors, which improves the trajectory tracking performance of the flexible manipulator [2]. In order to solve the problem that the trajectory-tracking performance of the manipulator under vibration basis is not high, Guo Yufei proposed a control method combining the new logarithmic power-reaching law with the fast terminal sliding-mode surface, and realized accurate trajectory-tracking of the manipulator within a limited time [3]. In order to suppress the residual vibrations of the forging robot caused by the forging press impact, Yuan Mingxin proposed a vibration-suppression strategy, combining input shaping and sliding modes, and verified the effectiveness of the strategy [4]. Huang Hua proposed an adaptive fuzzy sliding-mode control scheme to improve the trajectory-tracking accuracy of the two-link flexible manipulator and suppress vibration, and proved that the scheme is more effective than the PID controller and the traditional sliding-mode controller [5]. In order to solve the problem of vibrations in the hydraulic suspension system caused by random input excitation and long-term use, Gu Jianhua proposed a hybrid sliding-mode controller, which was proved by experiments to effectively suppress hydraulic suspension vibrations caused by disturbance excitations [6]. Suksabai and Nattapong proposed an input shaping control based on sliding-mode design to reduce the residual vibration of cranes under uncertain parameters [7]. Xiao Zhiying designed a self-tuning fuzzy sliding-mode controller to adjust the scale factor of the controller online. The experimental results show that the controller significantly improves the vibration-suppression and ride quality of the vehicle [8]. Qiu Zhiqiang proposed a sliding-mode neural-network fuzzy control method to suppress the vibration of the coupled double-flexible-beam system, and experiments showed that the control method has advantages in suppressing the large amplitude and low amplitude of the coupled double-flexible-beam system [9]. To further improve the target-tracking efficiency of the snake robot, Liu Zhifan proposed an improved double-power-reaching law and verified the effectiveness and practicability of the proposed strategy through comparative analysis and simulation [10]. Xu Yingming proposed a robust adaptive dynamic programming (RADP) method and a robust sliding-mode control (RSMC) method to control the two subsystems of the system in order to suppress the vibration of the flexible manipulator with variable loads. The proposed robust sliding-mode control can improve the vibration suppression at a fast time-scale, and the effectiveness of the algorithm was verified by simulation experiments [11]. In order to solve the problem that the free-floating flexible space manipulator affects the control accuracy and causes vibrations, Xie Limin proposed a robust fuzzy sliding-mode control for the slow subsystem to realize the tracking of the desired trajectory. For the fast subsystem, a velocity feedback control and linear quadratic optimal control were designed to suppress the vibrations caused by the flexible joint and the flexible connecting rod, respectively. The effectiveness of hybrid control is verified by simulation experiments [12]. In order to suppress the vertical vibration of new indoor bridge crane, Guo Donghuang proposed a robust integral sliding-mode control algorithm and showed, through simulation experiments, that the algorithm could effectively reduce the vertical vibrations of cargo [13].

The existing control algorithms are mainly oriented to general industrial robots, but there is little research on the control of a class of special-equipment robots with long arms and heavy loads, studied in this paper. The performance of PID control algorithm is relatively poor when the long telescopic arm of a heavy-duty robot with a long arm has deformations and vibrations in the process of movement. Traditional sliding-mode controllers

rely too much on models. However, the convergence speed of neural network control algorithm is slow, so it is not suitable for this kind of engineering application. Based on the above problems, this paper proposes a new sliding-mode controller based on the power hybrid reaching law. The stability of the controller is proved by the Lyapunov method, and a hybrid controller is formed by combining the force/position hybrid control and the force-based impedance control. Finally, the long-arm heavy-duty robot is simulated. The simulation results show that the designed controller can effectively reduce the amplitude of the long-arm heavy-duty robot.

The rest of this article is as follows. In the Section 2, the mechanism of the long-arm heavy-duty robot is analyzed and the kinematics and dynamics modeling of the robot are introduced. The Section 3 introduces the control scheme of the long-arm heavy-duty robot. In Section 4, a new power hybrid sliding-mode controller is proposed. In addition, in order to verify the effectiveness of the proposed controller's ability to suppress the vibrations of the long-arm heavy-duty robot, in Section 5, the two-stage telescopic boom is flexible, and the long-arm heavy-duty robot is simulated. To make the long-arm heavy-duty robot more compliant, a force-based impedance controller is added, and a simulation experiment is carried out to provide a reference for engineering parameter adjustment. Finally, the results are given in Section 6.

The main contributions of this paper are as follows:

- (1) In order to facilitate the control of long-arm heavy-duty robot, a hybrid force/position control and force-based impedance control scheme are proposed.
- (2) In order to solve the problem that the long telescopic arm of the long-arm heavy-duty robot faces deformations and the end-effector vibrates in the process of movement, a new power hybrid sliding-mode controller is proposed, and a strict mathematical proof is given by the Lyapunov method to verify the stability of the proposed controller. The effectiveness of the proposed power hybrid sliding-mode control is proved by comparing it with the simulation experiments of many new sliding-mode controllers.

2. Hybrid Force/Position Control Scheme

The hybrid force/position control strategy [14] is the idea of simultaneously using a position controller and force controller for control, as shown in Figure 1. For robots facing multiple degrees of freedom, the selection matrix S and $(I - S)$ can be introduced to determine the control mode of each joint. The selection matrix S and $(I - S)$ can be regarded as an interlock switch, as shown in Figure 1. In the position space, the position S with element 1 in the $(I - S)$ matrix has the corresponding element 0 in the matrix. The same is true in the force space.

To resolve the end-effector chattering in the palleting process for long-arm heavy-duty robots, more attention is paid to position control in the actual process of palleting. Therefore, for the lifting amplitude of the fixed arm of long-arm heavy-duty robots, the expansion of the two-stage telescopic arm and the swing amplitude of the end-effector in the process of palleting, the position space of the long-arm heavy-duty robots is controlled by the sliding-mode control algorithm. Impedance control based on force is used in the position space to change the difference between the actual position and the expected position of the end-effector into the force deviation. The position difference of the end-effector is reduced by adjusting the position of the end-effector indirectly through the impedance force. The latter two joints, which have little effect on the chattering of the end-effector, are controlled by the PD computational force, so the following hybrid force/position control law is adopted:

$$\tau = SJ^{+T}(q)(F_p + F_I) + (I - S)J^{+T}(q)F_f \quad (1)$$

$$M_d(\ddot{x}_d - \ddot{x}_e) + B_d(\dot{x}_d - \dot{x}_e) + K_d(x_d - x_e) = F_d - F_e \quad (2)$$

where S is the selection matrix, τ is the joint control torque, F_p is the Cartesian force of the sliding-mode controller, F_I is the impedance force, F_f is the Cartesian force output by

the PD controller, F_e is the actual force of the end-effector robot, F_d is the expected force of the end-effector robot, J is the Jacobian matrix, M_d is the inertia matrix, B_d is the damping matrix, K_d is the stiffness matrix, x_d is the Cartesian ideal trajectory and x_e is the actual Cartesian trajectory.

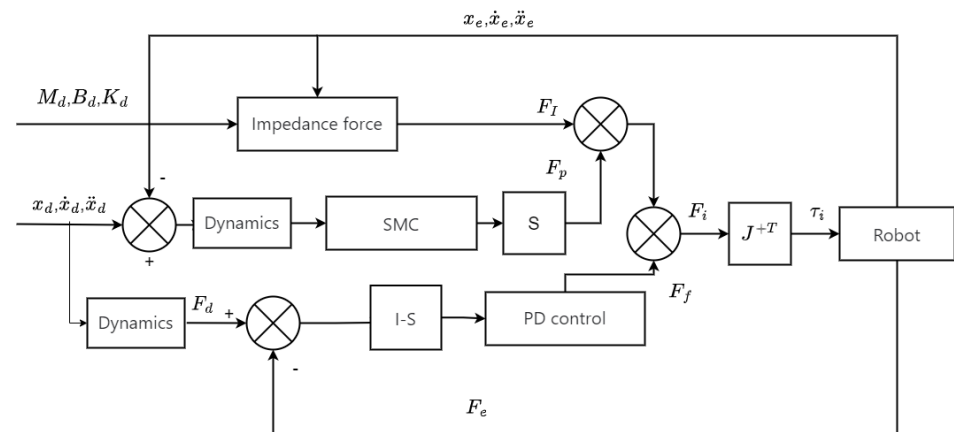


Figure 1. Schematic diagram of hybrid force/position control.

3. Kinematics and Dynamics Model of Long-Arm Heavy-Duty Robot

The research object of this paper is a loading robot with a double-open-chain structure with a long telescopic arm and heavy load. As shown in Figure 2, the main chain and auxiliary chain move each other to complete the work of the loading robot [15]. However, when the main chain and auxiliary chain are studied together, the difficulty of the research is greatly increased. In addition, in the loading robot design, the main chain is designed for high levels of travel and to improve the ability to manage heavy loads, and the secondary chain is designed to exchange smaller prismatic joint-driving forces for larger revolute joint-driving torque. In order to facilitate the study, the kinematics and dynamics of the main chain of the loading robot are modeled in this paper.

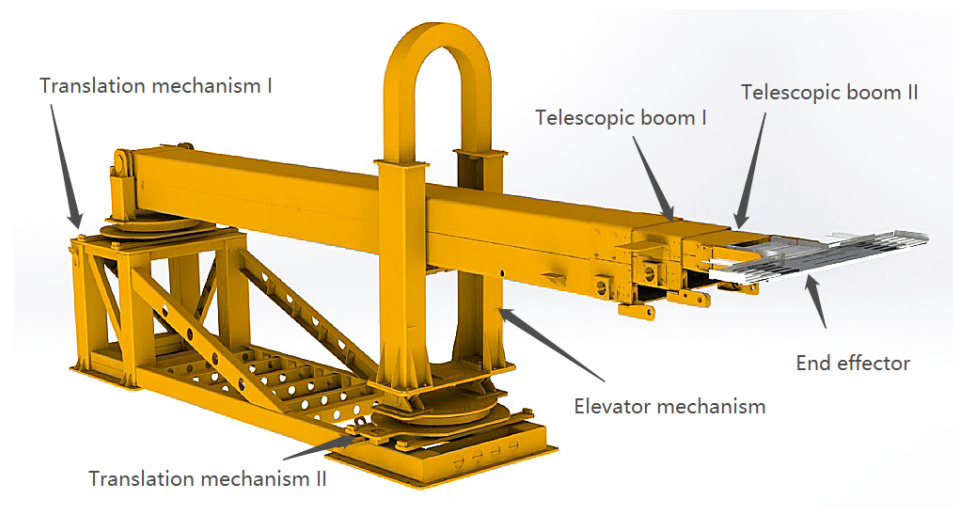


Figure 2. Model and actual picture of loading robot.

3.1. Long-Arm Heavy-Duty Robot Model

3.1.1. Kinematics of Heavy-Duty Robots with Long Arms

Establishing the kinematics of long-arm heavy-duty robots is the basis of the research on long-arm heavy-duty robots. In Figure 3, each joint of the loading robot is simplified into a connecting rod, and a coordinate system is established at the connection of each joint. In Table 1, the kinematic model of the loading robot is established using the modified DH [16]

(modified Denavit–Hartenberg, (MDH)) parameter method, where α_{i-1} represents the joint angle between two adjacent joints, a_{i-1} represents the distance between two adjacent rotation axes and d_i represents the distance between the joint axis from a connecting rod coordinate system to the connecting rod coordinate system. θ_i represents the rotation angle of one link with respect to the joint axis of another link.

Table 1. Kinematics parameters of MDH.

i	α_{i-1} [°]	a_{i-1} [mm]	d_i [mm]	θ [°]
1	0	a_0	q_1	90
2	90	0	d_2	q_2
3	90	0	0	q_3
4	90	0	q_4	0
5	0	a_5	q_5	0
6	90	0	0	0

According to the basis of robot mechanisms, the general expression of the homogeneous transformation matrix of the robot-generalized connecting rod is as follows:

$$T_i^{i-1} = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & 0 & a_{i-1} \\ \sin \theta_i \cos \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & -\sin \alpha_{i-1} & -d_i \sin \alpha_{i-1} \\ \sin \theta_i \sin \alpha_{i-1} & \cos \theta_i \sin \alpha_{i-1} & -\sin \alpha_{i-1} & -d_i \cos \alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

According to Formula (3), the homogeneous transformation matrix between the robot base and the fixture can be obtained:

$$T_6^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 T_6^5 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

From Formula (4), we can obtain the position and attitude of the end-effector of the loading robot relative to the base mark. The forward kinematics of the loading robot are described above.

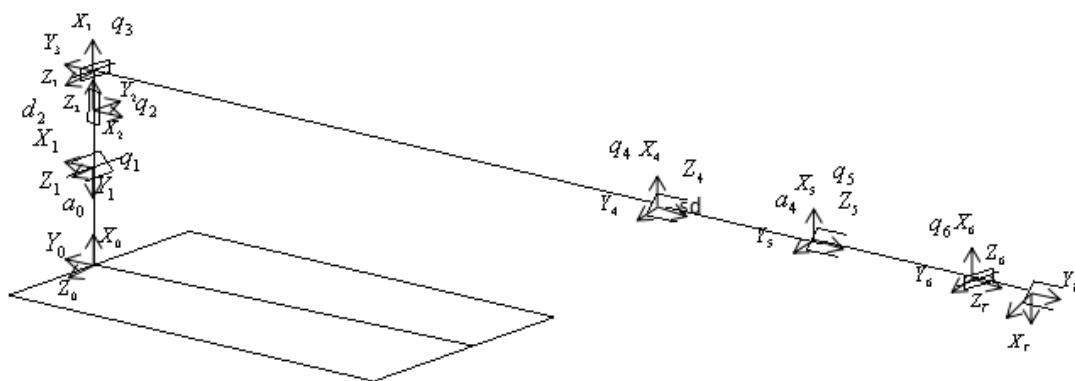


Figure 3. Connecting rod coordinate system of the main chain of long-arm heavy-duty robots.

3.1.2. Dynamics Model of Long-Arm Heavy-Duty Robot

Lagrange equations [17] and Newton–Euler methods are commonly used to model the dynamics of robots. In this paper, the Lagrange equation [18] is used to establish the dynamic equation of long-arm heavy-duty robots. It is considered that there is friction between the joints of long-arm heavy-duty robots in practical work, and lubricating oil

should be added regularly between the telescopic arms. Therefore, the dynamics model of a long-arm heavy-duty robot can be established as follows:

$$D(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + f_v\dot{q} + f_s\text{sign}(\dot{q}) = \tau \quad (5)$$

where q , $\dot{q}$, $\ddot{q}$ and are the joint position, velocity and acceleration in joint space of the robot, respectively; $D(q)$ is the inertia matrix of the robot; $C(q, \dot{q})$ are the centrifugal force and Coriolis force matrix of the robot, respectively; $G(q)$ is the gravity term of the robot; f_s is the Coulomb friction coefficient and f_v is the viscous friction coefficient.

In order to control the end position of the robot, it is necessary to convert the joint space dynamics equation into Cartesian space dynamics equation through the Jacobian matrix [19]. Based on the virtual work principle:

$$\tau_p = J_F^T(q)F_x \quad (6)$$

where τ_p is the joint torque from the position space, J_F^T is the Jacobian matrix; F_x is the force between the robot end-effector and the environment. Although the long-arm heavy-duty robot has six joints, joint 4 and joint 5 actually belong to the same degree of freedom, so the pseudo-inverse matrix $J^+(q) = [J_F^T(q)J_v(q)]^{-1}J_F^T(q)$ needs to be constructed. Therefore, $\dot{q} = [J_F^T(q)J_v(q)]^{-1}\dot{x}$, $\ddot{q} = \dot{J}_v(q)\dot{x} + J_v(q)\ddot{x}$. Therefore, the above equation is substituted into the dynamic equation in joint space. Accordingly, the dynamic equation of the long-arm heavy-duty robot in Cartesian coordinate system is:

$$D(q)_x\ddot{x} + C_x(q, \dot{q})\dot{x} + G_x(q) + F_{vx}\dot{x} + F_{sx}(\dot{q}) = F_x \quad (7)$$

where $D(q)_x = J^{+T}(q)D(q)J^+(q)$, $C_x(q, \dot{q}) = J^{+T}[C(q, \dot{q}) - D(q)J^+(q)]J(q)$, $G_x(q) = J^{+T}G(q)$, $F_{vx} = J^{+T}(q)f_vJ(q)$, $F_{sx} = J^{+T}(q)f_s\text{sign}(\dot{q})$, $\dot{x}$ and $\ddot{x}$ are the joint velocity and acceleration of the robot in Cartesian space, respectively.

The dynamic equation of a long-arm heavy-duty robot has the following two characteristics:

Property 1: The inertia matrix $D_x(q)$ is symmetric and positive definite.

Property 2: The matrix $\dot{D}_x(q) - 2C_x(q, \dot{q})$ is skew symmetric [17].

4. Design of a New Power Hybrid Sliding-Mode Controller

4.1. New Power Mixed Sliding-Mode Reaching Law

According to the long-arm heavy-duty robot model described in Section 2, tracking error e is defined as:

$$e(t) = x_d(t) - x_e(t) \quad (8)$$

$$\dot{x}_r = \dot{x}_d(t) + \Lambda e(t) \quad (9)$$

where, x_d is the Cartesian ideal trajectory, x_e is the Cartesian actual trajectory, $\dot{x}_d$ is the Cartesian ideal velocity and Λ is the positive definite matrix.

Under the condition that sliding-mode motion exists, the linear sliding-mode surface is defined as follows [20]:

$$s(t) = \dot{x}_r(t) - \dot{x}(t) = \dot{e}(t) + \Lambda e(t) \quad (10)$$

In order to suppress the system's inherent chattering under the traditional reaching law, a novel gain adaptive hybrid reaching law of variable exponential power is designed, whose expression is as follows:

$$\dot{s} = \frac{-qs - k_1\ln^{1+\alpha}(\epsilon s^v + 1)\text{sign}(s) - \mu|s|^\lambda\text{sign}(s)}{1 + \gamma e^{-k_2s}} \quad (11)$$

where $q > 0$; $k_1 > 0$; $k_2 > 0$; $\epsilon > 0$; $\mu > 0$; $\alpha > 0$; $0 < \lambda < 1$; v is positive.

The new power mixture reaching law adapts the sliding-mode gain according to the distance between the system state and the sliding-mode surface. When $|S|$ is large, $\gamma e^{-k_2 s}$ tends to 0, and the system reaching law is dominated by $-k_1 \ln^{1+\alpha}(\epsilon s^v + 1) \text{sign}(s) - qs$, which helps the system reach near the sliding-mode surface quickly. When $|S|$ is small, $\gamma e^{-k_2 s}$ tends toward γ and the system reaching law is dominated by $\frac{-\epsilon |S|^\lambda \text{sign}(s)}{1+\gamma}$, the sliding-mode gain is also less than the constant of ϵ when the system reaching law speed decreases. Therefore, a new power hybrid sliding-mode controller is designed:

$$F_r = D_x(q)\ddot{x}_r + C_x(q, \dot{q})\dot{x}_r + G_x(q) + \frac{qs + k_1 \ln^{1+\alpha}(\epsilon s^v + 1) \text{sign}(s) + \mu |s|^\lambda \text{sign}(s)}{1 + \gamma e^{-k_2 s}} \quad (12)$$

where F_r is the Cartesian force provided to the end-effector.

4.2. Lyapunov Stability Analysis

By substituting the new power hybrid sliding-mode controller into the dynamic equation of the long-arm heavy-duty robot, we obtain:

$$D_x(q)\ddot{s} + C_x(q, \dot{q})\dot{s} + G_x(q) + \frac{qs + k_1 \ln^{1+\alpha}(\epsilon s^v + 1) \text{sign}(s) + \mu |s|^\lambda \text{sign}(s)}{1 + \gamma e^{-k_2 s}} - \Delta f = 0 \quad (13)$$

where $s = \dot{x}_r - \dot{x}_e$, $\dot{s} = \ddot{x}_r - \ddot{x}_e$; $\Delta f = -F_{vx}\dot{x} - F_{sx}(\dot{q}) + f_{dis}$ is the friction mixed term and the uncertain term is not modeled.

Define the Lyapunov function:

$$V = \frac{1}{2} s^T D_x(q) s \quad (14)$$

Ince property 1 is known; then, $V > 0$, so V Lyapunov function is positive definite. The derivative of V yields:

$$\dot{V} = \frac{1}{2} s^T \dot{D}_x(q) s + s^T D_x(q) \dot{s} \quad (15)$$

As $\frac{1}{2} s^T \dot{D}_x(q) s = s^T C_x(q, \dot{q}) s$ is known from property 2 of the robot dynamics equation, substituting this into the above equation, we can obtain:

$$\begin{aligned} \dot{V} &= s^T D_x(q) \dot{s} + s^T \dot{C}_x(q, \dot{q}) s = s^T (D_x(q) + C_x(q, \dot{q})) s \\ &= s^T \left(\frac{-qs - k_1 \ln^{1+\alpha}(\epsilon s^v + 1) \text{sign}(s) - \mu |s|^\lambda \text{sign}(s)}{1 + \gamma e^{-k_2 s}} + \Delta f \right) \\ &\leq s^T \left(\frac{-qs - k_1 \ln^{1+\alpha}(\epsilon s^v + 1) \text{sign}(s) - \mu |s|^\lambda \text{sign}(s)}{1 + \gamma e^{-k_2 s}} \right) \\ &\leq \left(\frac{-qs^T s - k_1 \ln^{1+\alpha}(\epsilon s^v + 1) |s| - \mu |s|^\lambda |s|}{1 + \gamma e^{-k_2 s}} \right) \\ &\leq \left(\frac{-qs^T s - k_1 \ln^{1+\alpha}(\epsilon s^v + 1) |s| - \mu |s|^{\lambda+1}}{1 + \gamma e^{-k_2 s}} \right) \\ &\leq 0 \end{aligned} \quad (16)$$

$\dot{V}$ can be determined as semi-negative definite. According to Lyapunov's theory, the system could be globally asymptotically stable [21].

5. Simulation Platform Construction and Experimental Analysis

5.1. Simulation Platform Construction

MATLAB was used to model the dynamics of the long-arm heavy-load robot. In order to make the simulation experiment more consistent with the actual situation of deformation and jitter of the long-arm telescopic arm due to the characteristics of heavy load, the

two-stage telescopic arm was flexibly processed by ANSYS APDL [22]. In addition, the rigid telescopic arm was replaced with a flexible arm in ADAMS, and 2000 N force was added to the fixed arm and two-stage telescopic arm of the long-arm heavy-duty robot. Furthermore, 4000 N force was added to the end-effector, so that the simulation of the long-arm heavy-duty robot can be better combined with the actual working conditions, as shown in Figure 4. The overall control of the long-arm heavy-duty robot was carried out by MATLAB-ADAMS-ANSYS co-simulation, as shown in Figure 5.

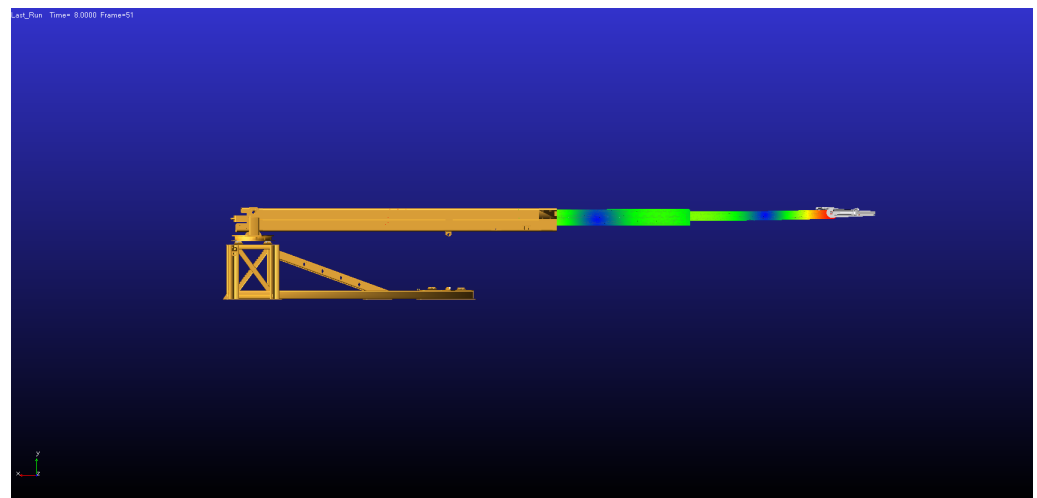


Figure 4. Actual structural performance diagram of heavy-duty robot with long arm.

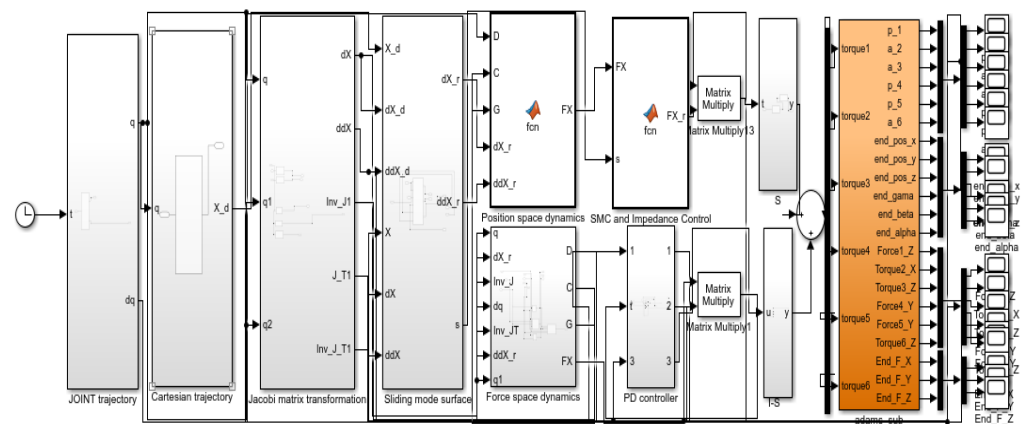


Figure 5. MATLAB-ADAMS-ANSYS co-simulation.

5.2. Simulation Experiment Analysis

The simulation experiment of the long-arm heavy-duty robot was set, the simulation time was set to 8 s and the simulation step was set to 0.005 s. The system joint state of the long-arm heavy-duty robot was set as $q_0 = [0, \pi, \pi/2, 420, 10164.85, -\pi]$, its mechanism parameters as $a_0 = 1392$ mm, $d_2 = 904$ mm, $a_5 = 31$ mm and the ideal trajectory of each joint as:

$$q = [0.2t^3, \frac{\pi \sin(t)}{1800000} + \pi, \frac{\pi \cos(t)}{1800000} + \frac{\pi}{2}, 7t^3 + 420, 7t^3 + 10164.85, \frac{\pi \sin(t)}{900000} + \pi] \quad (17)$$

In order to verify the effectiveness of the novel power hybrid sliding-mode controller (ALS), three new reaching laws and the new power hybrid reaching law sliding-mode control proposed in this paper were selected for simulation experiments under the condition that PD controller is used in the force space and the controller parameters are consistent. "DESIRE" was the ideal trajectory. The sliding-mode controller of the reaching law in [2]

is denoted as “AMM”; “SLL”, as in reference [23] and is the reaching law sliding-mode controller. “FMM”, as in [10], is the reaching law sliding-mode controller. The parameters $q = 35$, $k_1 = 5$, $\alpha = 0.2$, $\epsilon = 5$, $v = 2$, $\mu = 0.5$, $\gamma = 0.5$, $\lambda = 0.5$ and $k_2 = 0.8$ of the power function and the sliding-mode controller parameter $\Lambda = 0.001 * [1, 1, 10, 10, 10, 1]$ were used. After setting up the simulation experiment, the displacement change in the end-effector in Cartesian space when palletizing heavy loads was obtained in the initial pose of the long-arm heavy-duty robot.

For heavy-duty robots with long arms, the end-effector wobble in the direction perpendicular to the ground was the focus. As can be seen from Figure 6, the buffeting amplitude of the end-effector gradually decreased during the gradual expansion of the two-stage telescopic boom. In 1–3 s, due to the initial start-up of the robot, the robot tends to be stable after a small vibration in the initial stage. In the first 3 s, the telescopic length of the robot telescopic arm is short, and the telescopic arm has strong rigidity at this time. The telescopic arm did not show large deformations and vibrations, and the maximum position error was 11.65 mm. In the process of 3–6 s of transportation, the telescopic length of the robot’s telescopic arm gradually increases. At this time, the telescopic arm is more flexible and shows obvious deformation and vibration. The maximum vibration amplitude difference is 97.09 mm, which is 28.75%, 10.92% and 16.22% lower than the maximum amplitude difference in the AMM controller 136.27 mm, SLL controller 109 mm and FMM 115.89, respectively. In the 6–8 s transportation process, the maximum vibration amplitude of the telescopic boom was 70.17 mm, and in the late transportation, the vibration amplitude gradually decreased and tended to be stable. The vibration amplitude difference was about 6 mm. Compared with the other three controllers, this showed a better control performance and faster response.

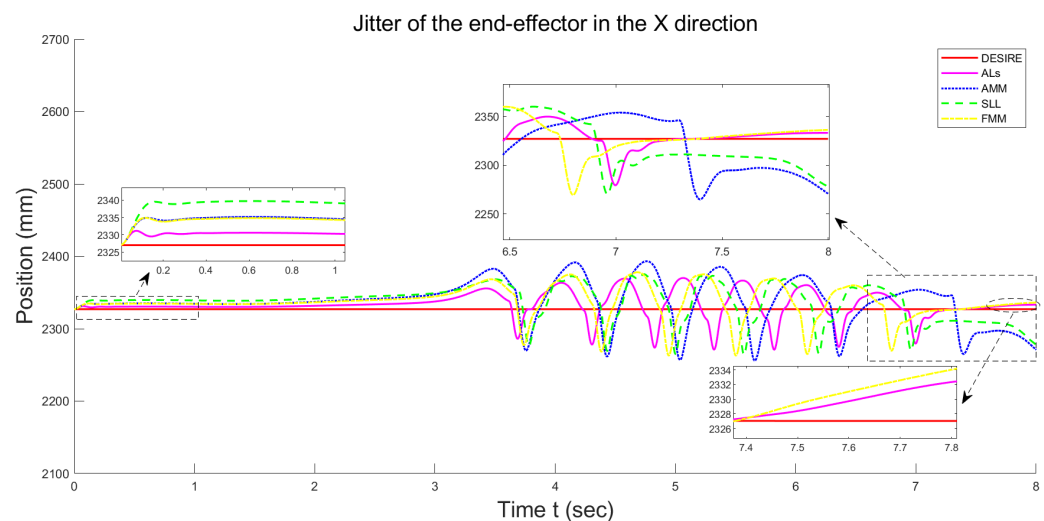


Figure 6. Jitter of the end-effector in the X direction.

Figure 7 shows the “depth” displacement diagram of the expansion arm of the end-effector extended into the container. As can be seen from the figure, the controller with the new power mixed-sliding-mode reaching law has a better effect on tracking the ideal trajectory than the other three reaching laws, and the vibration amplitude is effectively controlled. In 3–4 s, the vibration amplitude difference of the new power mixed reaching law sliding-mode controller is smaller in the end-effector jitter Y direction. When the controller gradually enters the steady-state stage in the later stage, the new power mixed reaching law is more stable and closer to the ideal trajectory than other reaching laws. At the same time, the new power mixture reaching law can enter the steady state earlier in the later motion.

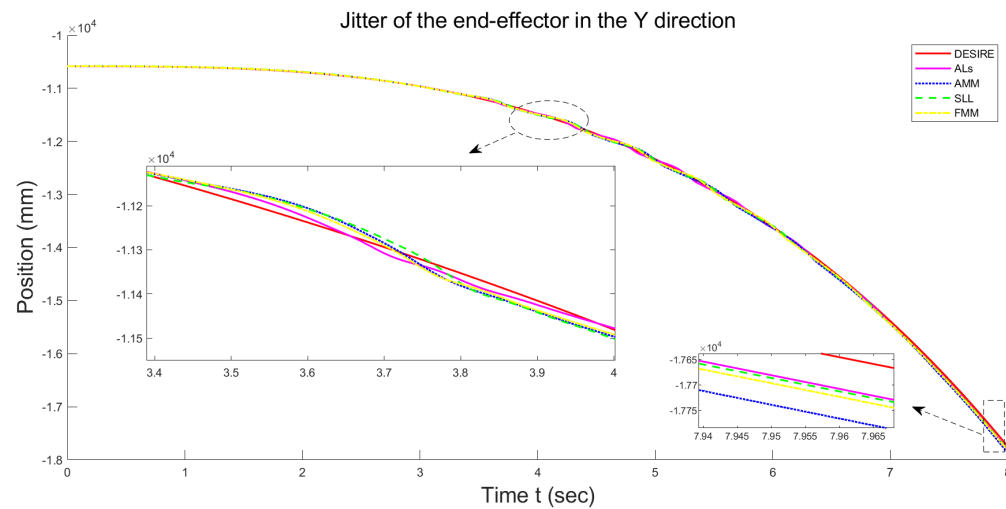


Figure 7. Jitter of the end-effector in the Y direction.

Figure 8 shows the displacement of the end-effector in the horizontal direction. Because the end-effector is stacked in the form of a whole row of goods after arriving at the stacking position, there is less movement in the horizontal direction for a long time. The maximum error between the tracking trajectory and the ideal trajectory of the reaching law in Figure 8 is about 15 mm, which is within the acceptable range.

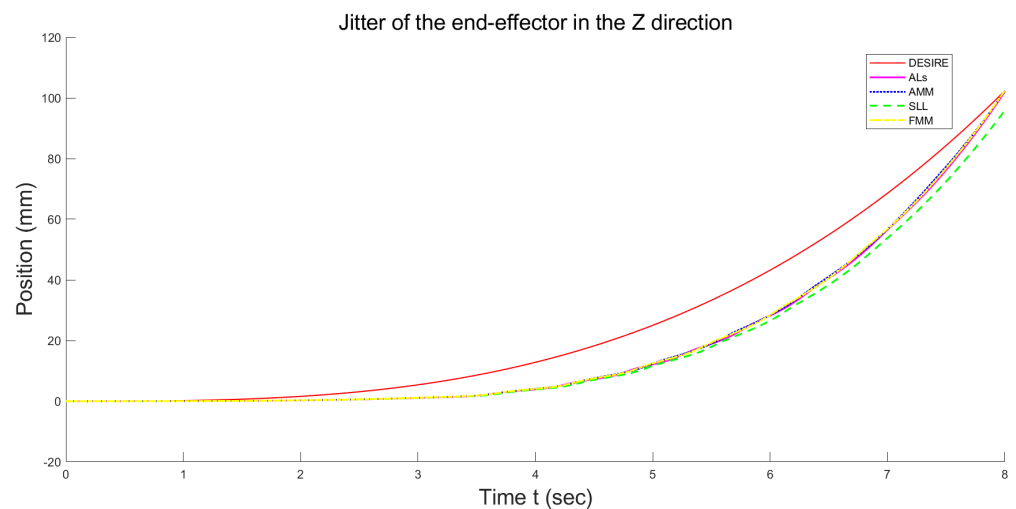


Figure 8. Jitter of the end-effector in the Z direction.

5.3. Impedance Control Simulation Experiment Analysis

The impedance controller was introduced to the force/position hybrid controller to make the heavy-duty robot with a long arm more compliant. On the basis of the previous section, the robot was simulated and analyzed to study the steady-state effects of M_d , B_d and K_d on the system. Therefore, the impedance parameters were individually modified and simulated, and the jitter of the end of the long-arm heavy-load robot in the X and Y directions was used to reasonably adjust the impedance parameters to achieve better compliance control.

5.3.1. The Influence of Stiffness Matrix K_d

The inertia matrix and damping matrix are $M_d = 5 \text{ kg}$ and $B_d = 5 \text{ s/m}$ respectively. As shown in the Figures 9 and 10, with the increase in stiffness matrix, the end-effector is

more able to suppress certain interference or jitter, the overshoot gradually decreases and the response speed is faster.

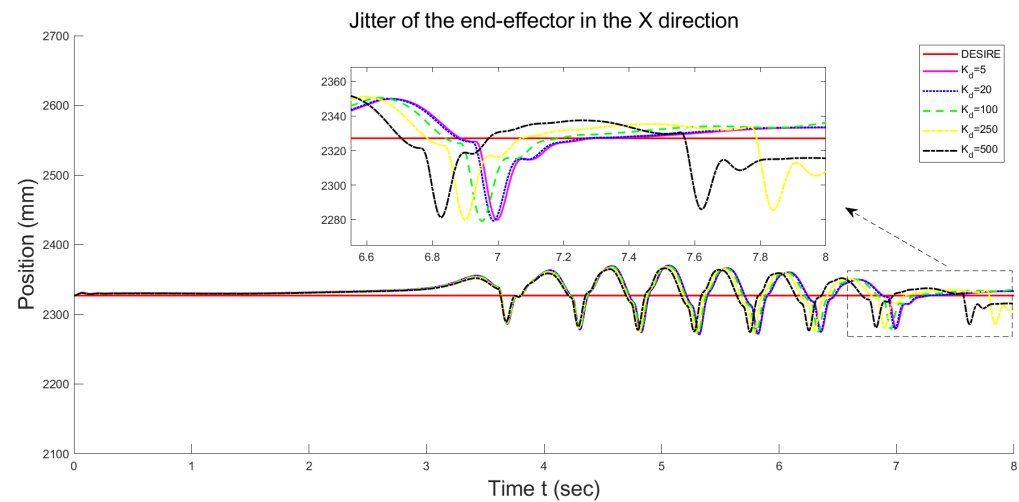


Figure 9. Influence of stiffness matrix parameter variation on end-effector in X direction.

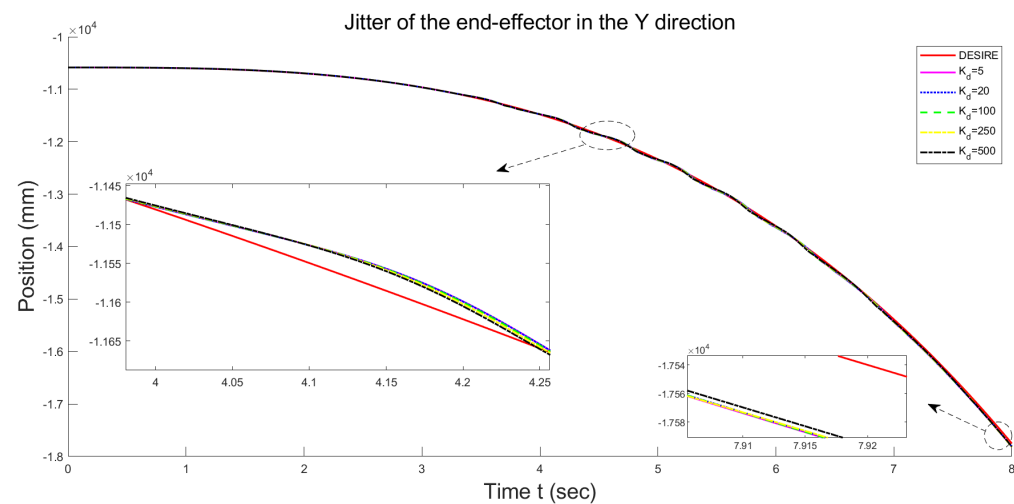


Figure 10. Influence of stiffness matrix parameter variation on end-effector in Y direction.

However, too large a stiffness coefficient will increase the oscillation frequency of the end-effector due to the faster response speed. Therefore, considering the flexibility characteristics of the long-arm heavy-duty robot, the comprehensive effect is better when $K_d = 100$ N/m is selected.

5.3.2. The Influence of STIFFNESS Matrix B_d

The inertia matrix M_d and stiffness matrix K_d were fixed as 750 kg and 100 N/m, respectively, the damping matrix was gradually tested from 50 Ns/m to 600 Ns/m, and the simulation results are shown in the figure. As can be seen from Figures 11 and 12, as the damping matrix gradually increases, the control system of the long-arm heavy-duty robot does not change significantly. Therefore, $B_d = 100$ Ns/m.

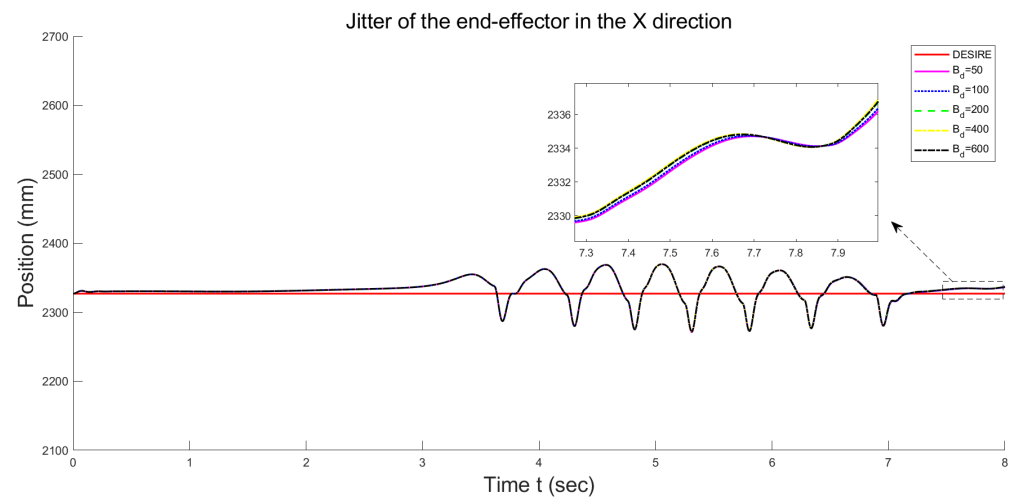


Figure 11. Influence of damping matrix parameter variation on end-effector in X direction.

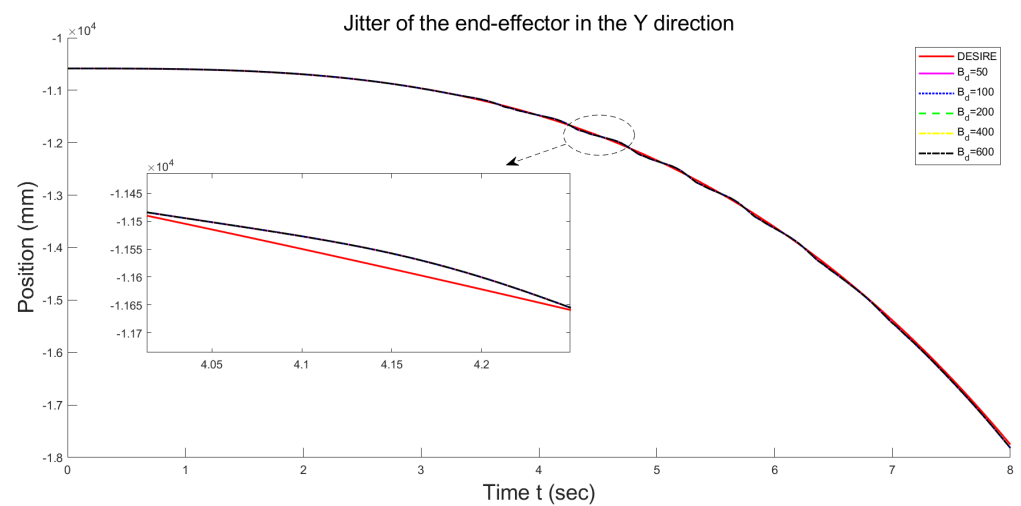


Figure 12. Influence of damping matrix parameter variation on end-effector in Y direction.

5.3.3. The Influence of Stiffness Matrix M_d

$B_d = 20$ s/m and $K_d = 100$ N/m were set as the fixed parameters of inertia matrix and damping matrix, respectively. The inertia matrix was tested step-by-step from 50 kg to 1000 kg, and the simulation results are shown in Figures 13 and 14. With the gradual increase in the inertia matrix parameters, the change in inertia parameters within a large range has no effect on the long-arm heavy-duty robot, but the increase in inertia parameters will slow down the transient response to a certain extent. Therefore, it is appropriate to choose $M_d = 500$ kg.

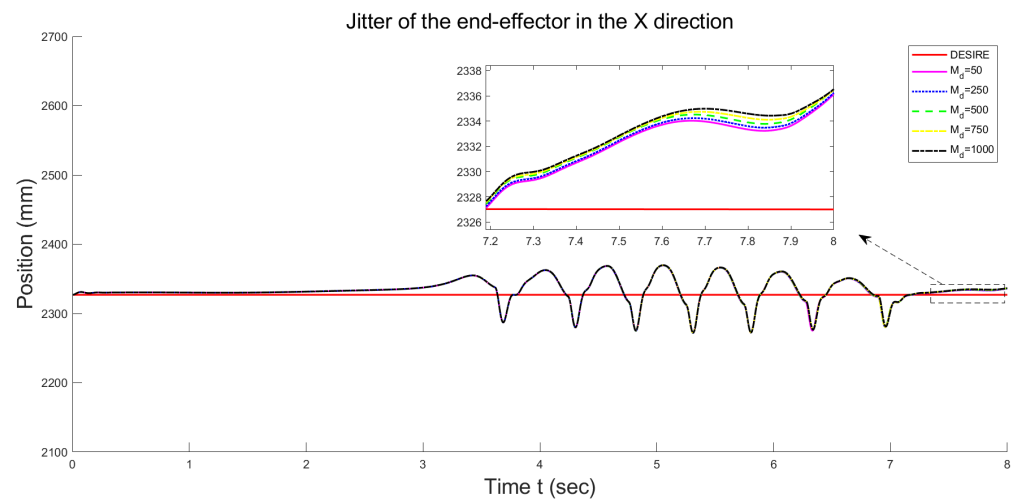


Figure 13. Influence of inertia matrix parameter variation on end-effector in X direction.

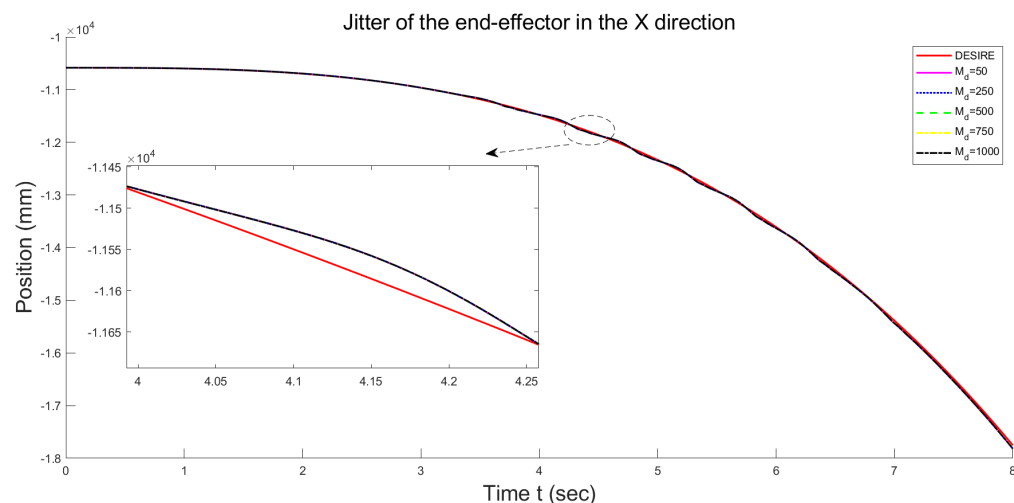


Figure 14. Influence of inertia matrix parameter variation on end-effector in Y direction.

6. Conclusions

In this paper, to solve the problem of low tracking accuracy and unstable movement of long-arm heavy-duty robots due to the deformations and vibrations caused by a long telescopic arm and heavy load, a hybrid control scheme of force/position and impedance is adopted, and a new power hybrid adaptive sliding-mode controller is proposed. The controller can adjust the gain according to the distance between the system and the sliding-mode surface, and improve the response speed of the system. The simulation results show that, compared with AMM, SLL and FMM controllers, the vertical and ground vibration amplitude of end-effector of long-arm heavy-duty robot are reduced by 28.75%, 10.92% and 16.22%, respectively. The controller can better reduce the amplitude difference of end-effector jitter and move towards a steady-state faster. Simulation results show that the new power hybrid reaching law sliding-mode controller has a better control performance, stronger robustness and faster response speed. Then, the force/position hybrid control and force-based impedance control are combined, and the optimal range of impedance controller parameters is determined by analyzing the influence of impedance control parameters on the long-arm heavy-duty robot, which provides a reference for practical engineering parameters. At the same time, the hybrid force/position and impedance controller designed in this paper provides a reference for the trajectory-tracking and vibration-suppression of the end-effector of a class of heavy-duty robots with long arms.

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