Configuration Selection and Vibration Analysis of Double Layer Suspended Cable-Driven Parallel Robot for Intelligent Storage System

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Abstract. Warehousing system plays an increasingly important role in the development of industry. However, the traditional warehousing system has the disadvantages of low efficiency, large space occupation and high maintenance difficulty, which has been unable to meet the needs of economic and social development. The demand for high efficiency and high stability intelligent storage system is more and more urgent. With the characteristics of large workspace and strong flexibility, suspended cable-driven parallel robot has great application potential in the field of intelligent storage. In this paper, the foundation of a two-layer suspended cable-driven parallel robot was proposed to meet the requirements of intelligent storage. Based on this foundation, a double layer suspended cable-driven parallel robot was established. The kinematics model of the double layer suspended cable-driven parallel robot was established, and the cable length curve in a motion period was obtained. Based on Hamilton's principle, the vibration model of the double layer suspended cable-driven parallel robot was established. The motion and vibration characteristics of the robot were analyzed in ADAMS, and the vibration law of the system was obtained.

Keywords: Intelligent storage · Suspended cable-driven parallel robot · Bilayer configuration · Vibration characteristics

1 Introduction

With the rapid development of national modernization, all kinds of factories, large-scale warehousing and logistics centers urgently need an intelligent warehousing system with high utilization rate and strong stability. In particular, the warehousing system has occupied a major position in the logistics link, which is related to the storage, distribution and information circulation of products, and has an increasingly important impact on the cost and efficiency of the entire industrial ecosystem. At the same time, the cost of human and land resources is rising, and the traditional storage system gradually shows the defects of low space utilization and low operation efficiency, which is difficult to meet the needs of economic and social development.

Therefore, the unmanned intelligent storage system has become a research hotspot, and the performance of the storage robot is directly related to the function realization of the storage system. In other words, in a warehouse center of the same scale, the more shelves there are, the stronger the ability of the storage system to store goods; the less storage robots are used, the higher the stability of the storage system. This requires the storage robot to have the characteristics of small size, no space occupation, multi-purpose and so on.

At present, the most widely used is the automatic guided vehicle (AGV) to carry goods [1, 2]. The guided vehicle to work normally, there should stick a magnetic stripe or two-dimensional code on the ground to form a preset path, and the robot will drive according to the preset path to complete the task. However, these two navigation methods not only have the problem of poor flexibility in path transformation, but also have the disadvantages of magnetic stripe and two-dimensional code easy to break, glue opening, pollution and so on [3]. And the storage center has the characteristics of large space and many kind of goods. Using a large number of automatic guided vehicles to carry goods, there will be problems such as difficult control, high cost, difficult maintenance and so on.

Compared with AGV, cable-driven parallel robot is suitable for working in large space, because the cable driven parallel mechanism has the characteristics of larger workspace and higher efficiency [4]. Cable-driven parallel mechanism is divided into full cable-driven parallel mechanism and suspended cable-driven Parallel mechanism [5]. Cable-driving parallel robot has be applied to the storage system [6, 7], but it only transfer goods to two shelves at most. For large storage centers, there are many robots needed, which still cannot meet the actual needs. Therefore, a double layer suspended cable-driven parallel robot is proposed in this paper, which has the characteristics of compact structure, strong flexibility and multi-function.

The double layer suspended cable-driven parallel robot is coupling superposition of flexible cables. Due to the characteristics of cables, the double layer system may have forced vibration, which affects the normal transportation of goods. Therefore, in view of the long-distance transportation of goods, it is necessary to analyze the vibration of the upper and lower layers respectively. The analysis method is similar to elevator transportation, they have similar vibration characteristics [9, 10], the partial differential equation of vibration of the double layer suspended cable-driven parallel robot is established based on Hamilton principle [11–13]. The simulation analysis is carried out by comparing the vibration process, which provides a theoretical support for the practical application of the double layer suspended cable-driven parallel robot.

2   Configuration Selection

For a large storage center, as shown in Fig. 1, the inbound robot places the goods carried by the inbound truck on the inbound conveyor belt, and the double layer suspended cable-driven parallel robot is responsible for the inbound operation; similarly, the double layer suspended cable-driven parallel robot places the goods to be outbound on the outbound conveyor belt, and the outbound robot places the goods on the outbound truck.
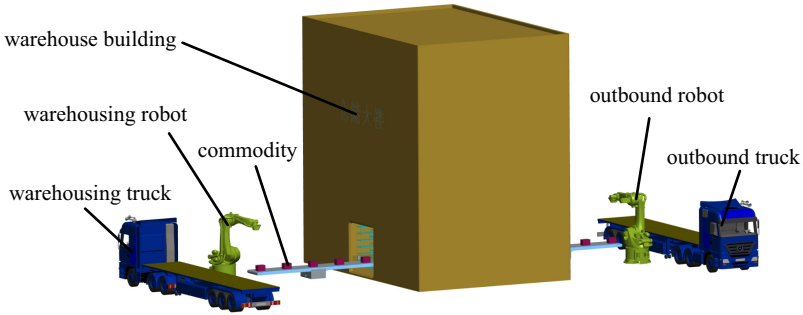
Fig. 1. Intelligent storage system

According to the design criteria of cable-driven parallel mechanism, the workspace of its moving platform is affected by the position of cable installation point [8]. However, the double layer suspended cable-driven parallel mechanism is quite special, because its gravity is equivalent to a cable moving in the same direction with the lower platform, so it is necessary to fully consider the accessibility of the lower platform position and the force on the cable during the task.

Based on the above analysis, this paper proposes the configuration basis of the double layer suspended cable-driven parallel robot for intelligent warehouse, as shown in Fig. 2a. The basic configuration of the double layer suspended cable-driven parallel robot is mainly composed of translation module and lifting module. The translation module controls the position of the lifting module in the X direction through the extension and shortening of the cable. However, since the translational module at any position has three attitudes, as shown in Fig. 2b, and the force and vibration of the cable in the translational module, it is necessary to add a stable cable based on this configuration to realize the translational function.
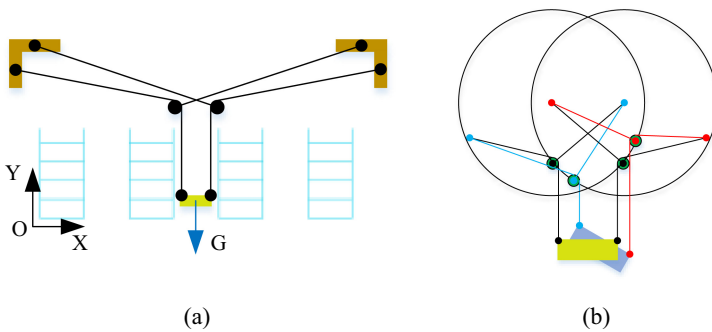

(a)   (b)

Fig. 2. Configuration basis of double layer suspended cable-driven parallel robot

According to the configuration foundation of the double layer suspended cable-driven parallel robot, two cables and a rigid beam are added to the translational module to realize stable translational function, as shown in Fig. 3a. At this time, the translational module

consists of four cables and a rigid beam, which is a stable and controllable configuration. According to the configuration of the double layer suspended cable-driven parallel robot, a double layer suspended cable-driven parallel robot for intelligent storage is designed, as shown in Fig. 3b. The robot consists of two groups of parallel module and lifting module, which ensures the balance of force on the platform, and reduces the deflection and vibration.
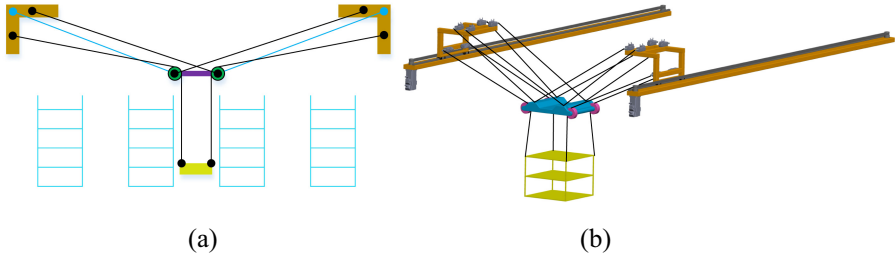

(a)   (b)

Fig. 3. Double layer suspended cable-driven parallel robot

3 Kinematic Analysis

The fixed coordinate system OXY of the robot is established in the middle of the cable connection point on the upper side of the translation module, as shown in Fig. 4. In the center of the moving platform of the translational module, the dynamic coordinate system oxy of the robot is established.
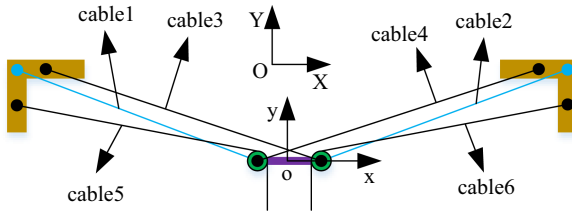

Fig. 4. Coordinate system of double layer suspended cable-driven parallel robot

Although the translational module is a redundant three degree of freedom mechanism, only one translational degree of freedom is used in this application, so the rotation matrix from the dynamic coordinate system to the static coordinate system of the double layer suspended cable-driven parallel robot is the identity matrix $\mathbf{E}$.

$$\mathbf{P}_i = \mathbf{E}\mathbf{n}_i + \mathbf{T} \tag{1}$$

$$L_i = \|\mathbf{E}\mathbf{n}_i + \mathbf{T} - \mathbf{m}\| \tag{2}$$

Where, P_i is the vector from the connection point of the cable of the moving platform of the translational module to the fixed coordinate system. n_i is the vector from the cable connection point of the translational module moving platform to the moving coordinate system. T is the vector from the moving coordinate system to the fixed coordinate system. m is the vector from the beam cable connection point to the fixed coordinate system. L_i is the length of the cable.

In order to facilitate the kinematic analysis, the following assumptions are put forward: in the kinematic analysis of the system, the elastic deformation of the cable is ignored, the sag caused by the dead weight of the cable is ignored, and the connection points of the cable are ideal spherical hinges.

The simulation content is a inbound delivery cycle, and the outbound delivery cycle is similar to it, which will not repeated. At the initial time, the lifting module is above the warehousing conveyor belt; from 0 s to 10 s, the lifting module descends; from 10 s to 20 s, the lifting module grabs and fixes the goods; from 20 s to 30 s, the lifting module rises to the translational track position; from 30 s to 40 s, the lifting module reaches the translational track position, The translation module moves the lifting module to the top of the gap between the two designated shelves; from 40 s to 50 s, the lifting module descends to the designated container of the designated shelf; from 50 s to 60 s, the lifting module pushes the goods out to the designated position; from 60 s to 70 s, the lifting module rises to the translation track; from 70 s to 80 s, the lifting module moves to the top of the warehousing conveyor belt. In this paper, cubic spline interpolation is used to fit the path to simulate the length of the cable, and the graph of the cable length with time is obtained, as shown in Fig. 5. Because the front and rear two groups of translation module and lifting module are the same, only one group of cable data can be used to represent.
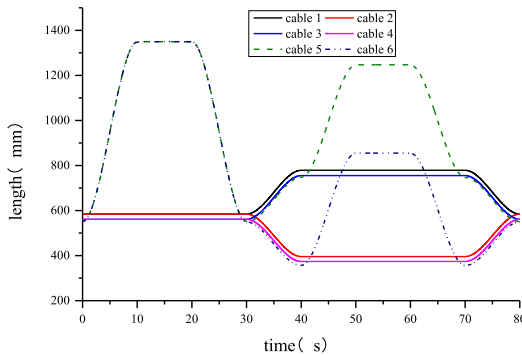

Fig. 5. The changing law of double layer suspended cable-driven parallel robot cable

4   Vibration Characteristics

Regardless of the resonance caused by the natural frequency, this paper studies the mechanical vibration caused by the change of the state of the cable itself. According to

the research, the longer the length of the flexible cable is, the smaller the stiffness is; The smaller the load, the smaller the stiffness [14]. The lifting module needs to provide a long-distance cargo displacement.

In the process of moving, the coupling of complex factors such as posture error of translational module moving platform, mutual influence between double layer cables, elastic deformation of cables and winding error will cause complex vibration of double layer cables cargo. In addition, there are transverse vibration and axial vibration in the cable, and the transverse vibration is ignored because the kinetic energy of transverse modal vibration accounts for only 0.01% [15].

However, in this paper, the cables are parallel and long, so the lateral vibration of the end load cannot be ignored. The vibration system will affect the cargo transportation function and the service life of the cable, so the research on the vibration of the double layer cable system is the premise to ensure the normal operation of the double-layer cable system. The system model of double-layer suspended cable traction parallel robot is established, as shown in Fig. 6.
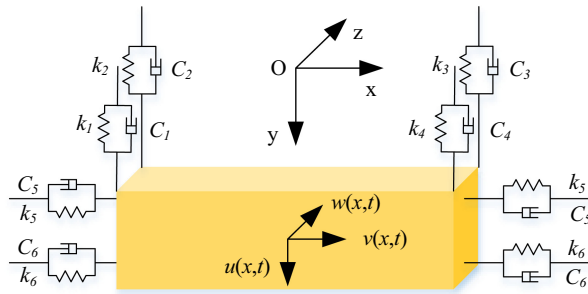

Fig. 6. Model of double layer suspended cable-driven parallel robot lifting system

The lifting module platform and the translational module platform are connected by springs with stiffness K_1, K_2, K_3 and K_4 and dampers with damping C_1, C_2, C_3 and C_4 respectively. The two sides of the loading platform and the shelf are connected by springs with stiffness of K_5 and K_6 and dampers with damping of C_5 and C_6 respectively to simulate the external excitation caused by the position and attitude error of translational module in the lifting state. The height of the lifting module loading platform is $2h$, the mass is m_c, the moment of inertia is J_c, the displacements in X, Y and Z directions are v_c, u_c, w_c, respectively, and the angular displacements are θ_c, respectively. The lateral displacements at the upper and lower ends of the loading platform are, v_5, v_6, respectively. The mass per unit length of each cable is ρ, the cross-sectional area is A, and the elastic modulus is E. During the movement of the loading platform, the length of the cable is $l_i(t)$, the longitudinal vibration on the cable $x(t)$ is $u_i(x, t)$, and the transverse vibration is $v_i(x, t)$. $\gamma(t) = \dot{l}(t)$ is the operating speed of the loading platform.

The geometric relationship between the lateral vibration displacement of the platform and the lateral displacement of the mass center can be equivalent to

$$\begin{cases} v_5 = v_c - h\theta_c \\ v_6 = v_c + h\theta_c \end{cases} \tag{3}$$

The kinetic energy of the system during the lifting process of the lifting module is

$$T = \sum \frac{1}{2}\rho \int_0^{l(t)} (\frac{Du}{Dt} + \gamma)^2 dx + \sum \frac{1}{2}\rho \int_0^{l(t)} (\frac{Dv}{Dt})^2 dx + \sum \frac{1}{2}\rho \int_0^{l(t)} (\frac{Dw}{Dt})^2 dx$$
$$+ \frac{1}{2}m_c(\dot{u}_c + \gamma)^2 + \frac{1}{2}m_c\dot{v}_c^2 + \frac{1}{2}J_c\dot{\theta}_c^2 \tag{4}$$

Where, differential operator $\frac{D}{Dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial x}$.

The elastic potential energy of the system during the lifting process of the lifting module can be written as:

$$V_e = \sum \frac{1}{2} \int_0^{l(t)} EA\varepsilon(x, t)^2 dx + \sum \frac{1}{2}k_i[u_c - u(l, t)]^2 + \frac{1}{2}(k_5v_5^2 + k_6v_6^2) \tag{5}$$

$$\varepsilon(x, t) = \sqrt{(1 + u_x)^2 + v_x^2} - 1 \approx u_x + \frac{1}{2}v_x^2 \tag{6}$$

During the lifting process of lifting module, the gravity potential energy of the system is defined as:

$$V_g = \int_0^{l(t)} \rho g[u(x, t) + x]dx + m_cg[u_c + h + l(t)] \tag{7}$$

The virtual work of the system damping force during the lifting process of the lifting module is

$$\delta W = \sum \int_0^{l(t)} (c_u\frac{Du}{Dt}\delta u + c_v\frac{Dv}{Dt}\delta v)dx + \sum C_i[\dot{u}_c - \frac{Du(l, t)}{Dt}][\delta u_c - \delta u(l, t)]$$
$$+ C_5\dot{v}_5\delta v_5 + C_6\dot{v}_6\delta v_6 \tag{8}$$

According to the generalized Hamilton principle, the system satisfies the equation

$$\int_{t_1}^{t_2} \delta(T - V_e + V_g - W)dt = 0 \tag{9}$$

The vibration equation of the loading platform during the lifting process of the lifting module is

$$\begin{cases} m_c\ddot{u}_c + \sum C_i(\dot{u}_c - \frac{Du(l,t)}{Dt}) + \sum k_i(u_c - u(l, t)) = m_c(g - \dot{\gamma}) \\ \frac{m_ch^2+J_c}{l_c^2}\ddot{v}_5 + \frac{m_ch^2-J_c}{l_c^2}\ddot{v}_6 + \sum EA\varepsilon(l, t)v_x(l, t) + C_5\dot{v}_5 + k_5v_5 = 0 \\ \frac{m_ch^2-J_c}{l_c^2}\ddot{v}_5 + \frac{m_ch^2+J_c}{l_c^2}\ddot{v}_6 + C_6\dot{v}_6 + k_6v_6 = 0 \end{cases} \tag{10}$$

According to the vibration equation and geometric relationship of the system, the transverse vibration of the platform is

$$\begin{cases} \sum \rho \frac{D^2 v}{Dt^2} - (\overline{p}(x,t)v_x)_x - \sum EA[(\tilde{u}_x + \frac{1}{2}v_x^2)v_x]_x + c_v\frac{Dv}{Dt} = 0 \\ \frac{m_c h^2 + J_c}{l_c^2}\ddot{v}_5 - \frac{m_c h^2 - J_c}{l_c^2}\ddot{v}_6 + [\overline{p}(l,t) + \sum EA(\tilde{u}_x + \frac{1}{2}v_x^2)]v_x(l,t) + C_5\dot{v}_5 + k_5 v_1 = 0 \\ \frac{m_c h^2 - J_c}{l_c^2}\ddot{v}_5 - \frac{m_c h^2 + J_c}{l_c^2}\ddot{v}_6 + C_6\dot{v}_6 + k_6 v_6 = 0 \end{cases}$$

$$(11)$$

$\overline{p}(x,t)$ is the static tension of the cable due to gravity at t.

According to the above analysis, the simulation model is established in ADAMS, as shown in Fig. 7. The kinematics results of the double layer suspended cable-driven parallel robot are used for simulation analysis. Taking 20 kg and 50 kg rectangular containers as an example, 1 kg high-strength lightweight engineering plastics is used for the translational module platform. The weight of the lifting module platform is 12 times that of the translational module platform, and the weight of the goods is 20 times and 50 times that of the translational module platform. Measure the position of the cable connection point of the moving platform of the translation module and the cable connection point of the loading platform of the lifting module.
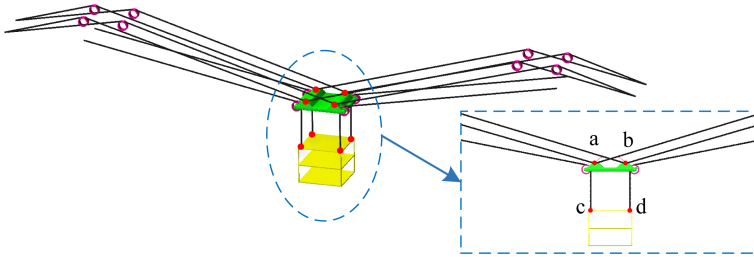

Fig. 7. ADAMS simulation model

To determine the vibration of the system, the motion of the measuring points of the translational module and the lifting module shall be measured, as shown in Fig. 8. In the figure, the attitude error of the moving platform of translational module exists in the process of cargo transportation, but there is no obvious vibration in the X direction; the lifting module loading platform has obvious vibration during the cargo transportation, starting from the movement of the 40 s translational module, and the vibration gradually increases. The main reason of vibration is the position error of the moving platform of the translational module.

In order to determine the pose change of the moving platform of the translational module, the measurement points a and b are measured, and the difference curve of a and b is obtained, as shown in Fig. 9. In the figure, the X-direction and Y-direction vibration of the translational module appears after the translational movement starts in 30 s; the vibration amplitude is the largest in the process of loading and unloading, that is, 30 s to 60 s. At the same time, the goods with 20 times moving platform mass have high

frequency vibration in Z direction after 40 s, on the contrary, the goods with 50 times moving platform mass have no vibration in Z direction.
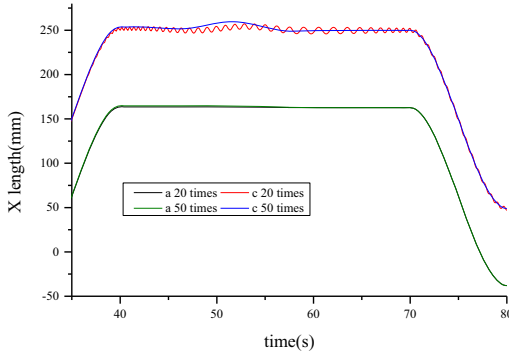
Fig. 8. Measure the displacement of points a and c in the X direction
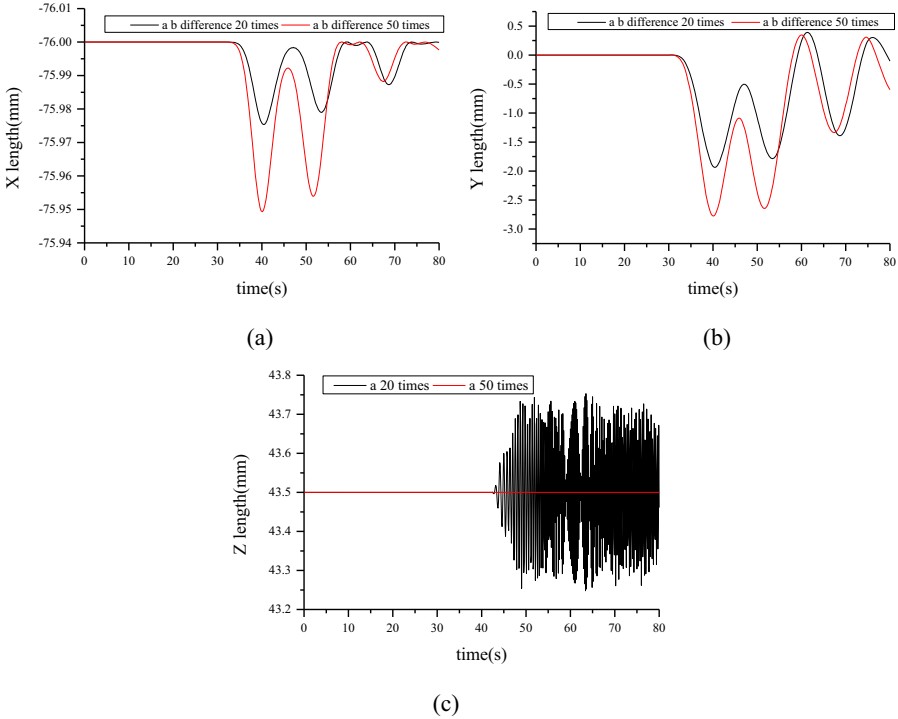
(a)

(b)

(c)

Fig. 9. The position relation of measuring points a and b

In order to determine the position and posture change of the lifting module loading platform, the measurement points c and d are measured, and the difference curve of c and d is obtained, as shown in Fig. 10.
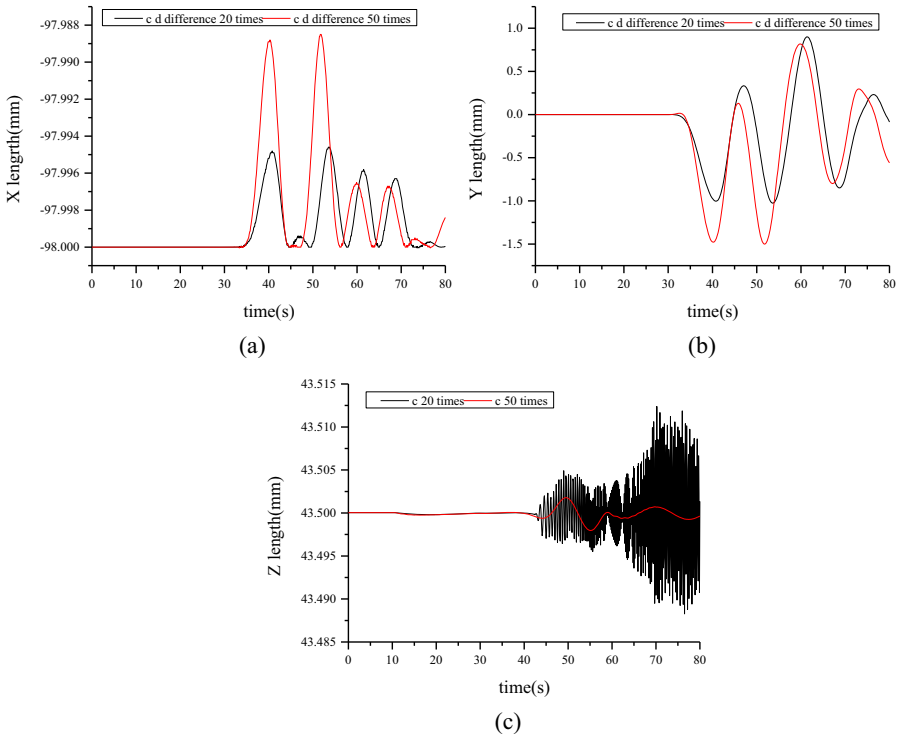
Fig. 10. The position relation of measuring points c and d

The vibration law of the lifting module in Fig. 10 is similar to that of the translational module above, and there is no significant difference in the amplitude. High frequency vibration also occurs in the process of 20 times the weight of the moving platform. The difference is that the Z direction of the cargo with 50 times the mass of the moving platform also vibrates.

5 Conclusion

The double layer suspended cable-driven parallel robot has good cargo transportation performance, which can meet the needs of large-scale intelligent storage center. Among them, the upper translation module of the double layer suspended cable-driven parallel robot has good stability and can provide accurate translation displacement. However, due to the different elastic deformation of the cable during the movement of the translational module, the pose error of the translational module platform is caused, which affects the normal operation of the lifting module. This problem can be solved by the follow-up force control strategy. Due to the long-distance displacement of goods provided by the lower lifting module of the double layer suspended cable-driven parallel robot, the vibration of the loading platform is difficult to avoid. However, appropriate control strategy can meet the requirements of keeping the vibration in a controllable range.

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