Design and Dynamic Analysis of Cleaning Robot for Cement Silos

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Abstract: Aiming at the mechanization and automation of cleaning the hardening on the wall of the cement silo, a silo cleaning robot is designed. The kinematics and dynamics mathematical models of the cleaning robot are established respectively. With the 12000mm diameter silo as the cleaning object, the dynamics model is constructed with virtual prototype. There is an analysis of the relationship between the angular velocity and angular acceleration of the mechanical arm, and the relationship between the thrust of the cylinder over time were analyzed. The results show that the calculation results of the mathematical model and the simulation model are close, the change trend is consistent, and the movement is stable and meets the design requirements, which verifies the correctness of the mathematical model. The research results provide a theoretical basis for the next step of control system design and strength analysis. This silo cleaning robot solution can be extended to the cleaning construction of other silos such as coal bunkers, granaries and ore silo.

1. Introduction
Cement storage is one of the important links in cement production. Cement silo in walls hardened will cause cement reserves to decrease, which requires regular silo cleaning [1-2].

The main method of silo cleaning is manual cleaning. Manual cleaning is when the construction personnel enter the warehouse to work at high altitude to clean the warehouse wall. It is often caused by the collapse of the warehouse to cause casualties. Moreover, due to the harsh working environment in the warehouse, dust flying, low oxygen content and other factors are extremely harmful to the health of the construction personnel [3]. At present, due to the complex structure and high cost of the cleaning robot, the research on it is not sufficient and it has not been widely used.

In order to solve the existing problems, this paper designs a cleaning robot with simple structure, convenient installation, transportation and storage, suitable for a variety of silo types, which can greatly improve work efficiency, solve the hidden dangers of construction personnel, and realize unmanned Warehousing. This study establish a simplified model by using this as the research object. The kinematics and dynamics mathematical models are established by using the vector analysis method and the Lagrange dynamics method through the theoretical analysis of the robot mechanism[4-5]. ADAMS simulation software was used to establish the simulation model and carry out the dynamics simulation, and then through the comparison and analysis with the theoretical model,
it is concluded that whether the angular velocity and angular acceleration of the mechanical arm meet the work requirements, and whether the calculation of the driving force of the cylinder is correct. The data is processed to obtain the deviation value, and the mathematical model is verified whether it is correct. Lay a theoretical foundation for the design and strength analysis of the control system.

2. Design and experimental verification of silo cleaning robot

2.1. The design of silo cleaning robot

This paper design a silo cleaning robot, which mainly supported by the platform, cylinder, mechanical arms, support rods and power devices. The design drawing of the silo cleaning robot scheme in Figure 1. The support platform is divided into upper and lower platforms for lifting, and the lower part is used as the support and fixing surface of the support rod and cylinder. The upper and lower parts are connected by three support rods through nuts; The cylinder is fixed to the supporting platform by the upper flange type cylinder flange; The mechanical arm is composed of multiple small mechanical arms connected by flanges; The length of each small mechanical arm is 2000mm, which is convenient for disassembly and transportation; both ends of the support rod are connected to the mechanical arm and the cylinder push rod through the pin shaft; the power device adopts The modified electric hammer is connected to the end of the mechanical arm through a bolt. The upper part is hoisted by the hoist on the top of the silo, and there is a slewing device under the hoist to realize the maneuver of the cleaning robot.

The way of using the silo cleaning robot is that the construction personnel install the robot section by section on the top of the silo, that is, from the power device to the mechanical arm to the support rod support platform, which are respectively connected by bolts and pins. After installation, the operator uses a hoist to lift the robot from the top inlet of the silo into the silo, and the system controls the cylinder to push the support rod. The support rod drives the mechanical arm to rotate around the hinge point of the support platform to make the power device installed at the end of the mechanical arm. Reach the position that needs to be cleaned, and clean up the hardening on the silo wall.

The advantages of this silo cleaning robot: 1) Realize that no one enters the warehouse to complete the cleaning of the silo, ensuring the life safety of the construction personnel; 2) There is no need to damage or modify the existing silo, and the silo can be directly installed on top of the silo. It is easy to install and use, it only needs a small number of operators, and the work efficiency is high; 3) The robot is installed section by section, and the whole machine does not need to be hoisted and placed at the construction site, which reduces the difficulty of construction and reduces the volume. Convenient for transportation and storage.

2.2. Experimental verification of silo cleaning robot

After completing the design of the silo cleaning robot, in order to verify whether the robot can
complete the cleaning of the hardening in the silo, a scaled down experimental device was built as shown in Figure 2. The experimental device does not contain control systems, and is only used to verify whether the device can meet the construction requirements, and the feasibility of the scheme is verified through experiments.

Figure 2 Experiment of silo cleaning device

3. Establishment of theoretical model of silo cleaning robot

For the silo cleaning robot, in order to facilitate the analysis and simplify the processing, because the robot is a symmetrical structure, the establishment and simulation analysis of the kinematics and dynamics mathematical model only need to analyze one-third, and the mechanical arm, support rod and power. The device is symmetrical about the XY plane, so the simplified diagram of the silo cleaning robot can be made as shown in Figure 3. The propulsion direction of the cylinder is the positive direction of the y-axis, and the hinge direction along the center of the support platform is the positive direction of the x-axis. The intersection point is a coordinate system whose origin is the intersection point D of the mechanical arm and the push rod of the cylinder. To facilitate the calculation and definition of the angle between each member, define the angle between the mechanical arm $L_{AB}$ and the support platform $L_{AD}$ as $\theta_1$, the angle between the support rod $L_{BC}$ and the cylinder push rod $L_{CD}$ as $\theta_2$, and the angle between the mechanical arm and the $L_{AB}$ support rod $L_{BC}$ as $\theta_3$. The cylinder push rod is always perpendicular to the support platform. In order to facilitate the definition of the size of each construction, as shown in Figure 4, the length of the support platform $L_{AD}$ is defined as $L_1$, the length of the mechanical arm $L_{AB}$ is defined as $L_2$, the length of the support rod $L_{BC}$ is defined as $L_3$, and the length of the $L_{CD}$ at the initial position of the cylinder is defined as $L_4$. Define the center of mass of the support rod as point E, and the center of mass of the mechanical arm as point F. The angle in the geometry of the mechanical arm is a fixed value, which is only related to its structure and has nothing to do with the movement of the mechanism. Define the angle between the mechanical arm $L_{AB}$ and $L_{AF}$ as $\eta_1$. 
3.1. Kinematics mathematical model establishment
Taking the speed $v$ of the cylinder as the input quantity, the position of point C under the coordinates is determined, and the functional relationship between each angle and time is solved according to the geometric relationship, as shown in Table 1.
Table 1  Functional relationship between angle and time

| Angle | Functional relationship |
|-------|-------------------------|
| \( \theta_1 \) | \( \theta_1 = \frac{3}{2} \pi - \theta_1 - \theta_3 \) |
| \( \theta_2 \) | \( \theta_2 = \arccos \left( \frac{L_2^2 + L_3^2 - (L_4 + \omega t)^2}{2L_4(L_3 + \omega t)} \right) + \arctan \left( \frac{L_3}{L_4 + \omega t} \right) \) |
| \( \theta_3 \) | \( \theta_3 = \arccos \left( \frac{L_2^2 + L_4^2 - (L_4 + \omega t)^2}{2L_4L_3} \right) \) |

Obtain the first derivative of \( \theta_2 \) with respect to time in Table 1 to obtain the angular velocity \( \omega_2 \) of the support rod, and calculate the second derivative of \( \theta_2 \) with respect to time in Table 1 to obtain the angular acceleration \( \alpha_2 \) of the support rod.

Use vector analytic methods to establish closed equations. It can be obtained that the component form of the closed equation of the angular displacement vector projected on the X axis is:

\[
L_2 \cos(\pi - \theta_1) + L_4 = L_4 \sin(\pi - \theta_2)
\]

(1)

The angular displacement vector component equation calculates the first derivative with respect to time, and the angular velocity can be obtained as:

\[
\omega_1 = \frac{\omega_2 L_3 \cos \theta_2}{L_3 \sin \theta_1}
\]

(2)

The angular displacement component equation calculates the second derivative with respect to time, and the angular acceleration can be obtained as:

\[
\alpha_1 = \frac{\alpha_2 L_3 \cos \theta_2 - \omega_2^2 L_4 \sin \theta_1 - \omega_2 \omega_1 L_2 \cos \theta_1}{L_2 \sin \theta_1}
\]

(3)

3.2. Dynamic mathematical model establishment

The purpose of dynamic analysis is to study the relationship between the thrust of the cylinder and the parameters and time of each mechanism. In this paper, Lagrange's equation is used to analyze the dynamics of the cleaning robot. According to the position of the mechanism in Figure 3 and Figure 4, the center of mass coordinates and the center of mass velocity of the mechanical arm and the support rod are as shown in Table 2.

Table 2  Center of mass coordinates and the center of mass velocity

| Part          | Center of mass coordinates | Center of mass velocity |
|---------------|----------------------------|-------------------------|
| **Support rod** | \( x_c = L_4 - L_2 \cos \theta_1 - L_3 \sin \frac{\theta_1}{2} \) \n \( y_c = L_2 \sin \frac{\theta_1}{2} + L_3 \cos \frac{\theta_1}{2} \) | \( \dot{x}_c = \omega_1 L_2 \sin \theta_1 - \frac{\alpha_2 L_3 \cos \theta_1}{2} \) \n \( \dot{y}_c = \omega_1 L_2 \cos \theta_1 - \frac{\alpha_2 L_3 \sin \theta_1}{2} \) |
| **Mechanical arm** | \( x_f = L_4 - H \cos(\theta_1 + \eta_1) \) \n \( y_f = H \sin(\theta_1 + \eta_1) \) | \( \dot{x}_f = \omega_1 H \sin(\theta_1 + \eta_1) \) \n \( \dot{y}_f = \omega_1 H \cos(\theta_1 + \eta_1) \) |

Where: \( \eta_1 \) - the angle \( \eta_1 \) between the mechanical arm \( L_{AB} \) and \( L_{AF} \), take \( \eta_1 = 4.623^\circ \).

According to the coordinates of the center of mass and the speed of the center of mass of the mechanical arm and the support rod in Table 2, the kinetic energy and potential energy of the mechanical arm and the support rod are as shown in Table 3.
Table 3 Kinetic energy and potential energy

| Part          | Kinetic energy                                      | Potential energy                               |
|---------------|-----------------------------------------------------|-------------------------------------------------|
| Mechanical arm| $T_i = \frac{1}{2}J_1\omega_i^2 + \frac{1}{2}m_1(x_i' + y_i')^2$ | $V_i = m_1g\left(L_1\sin\theta_1 + \frac{L_1\cos\theta_1}{2}\right)$ |
| Support rod   | $T_i = \frac{1}{2}J_2\omega_i^2$                   | $V_i = m_2gH\sin(\theta_1 + \eta_1)$            |

Where: $J_1$ - the moment of inertia of the mechanical arm, take $J_1 = 3.293 \times 10^9 \text{kg} \cdot \text{mm}^2$; $J_2$ - the moment of inertia of the support rod, take $J_2 = 2.139 \times 10^7 \text{kg} \cdot \text{mm}^2$; $m_2$ - the mass of the support rod, take $m_2 = 20.787 \text{kg}$; $m_1$ - the quality of the mechanical arm, take $m_1 = 181.276 \text{kg}$.

4. Simulation modeling and analysis of cleaning robot

4.1. Simulation model establishment
This paper selects a silo with a diameter of 12000mm as the application object, and uses SolidWorks software to establish a three-dimensional model of a silo cleaning robot corresponding to the silo type [6]. The main dimensions, initial positions and material densities of each component are shown in Table 4. Then import the model into the virtual prototype software ADAMS[7], and add material properties (this mathematics model analysis ignores the gravity of the cylinder push rod, in order to make the analysis more accurate, the simulation model sets the cylinder push rod force density to 0).

Table 4 Main dimensions, initial positions and material densities of each component

| Part | Initial size (L/mm) | Material                  | Densities ρ (kg/mm³) |
|------|---------------------|---------------------------|----------------------|
| L₁   | 155                 | Ordinary carbon steel     | 7.8×10¹²             |
| L₂   | 1792                | Ordinary carbon steel     | 7.8×10¹²             |
| L₃   | 1750                | Ordinary carbon steel     | 7.8×10¹²             |
| L₄   | 40                  | Ordinary carbon steel     | 7.8×10¹²             |

The main types of its motion pairs are rotating pairs and moving pairs. Set the translation drive to act on the cylinder. The cylinder push rod is moving down at 17.91 mm/s, so that the virtual prototype runs at the required design speed. Set the simulation time to 20s to make the mechanical arm rotate from the initial position to the position where the angle with the horizontal is 0.524rad. The number of steps is 50, and the analysis type adopts kinetics.

4.2. Simulation results and analysis
Taking the cylinder propulsion speed as the control object, the simulation results of the angular velocity and angular acceleration of the mechanical arm changing with time are solved, and the
simulation results of the cylinder thrust changing with time are solved. The simulation results are compared and analyzed with the theoretical results to verify the correctness of the mathematical model. The comparison of the results is shown in Figure 5 and Figure 6.

![Figure 5 Comparison chart of angular velocity of mechanical arm over time](image1)

![Figure 6 Comparison chart of angular acceleration of manipulator arm over time](image2)

![Figure 7 Comparison chart of cylinder thrust over time](image3)

It can be seen from Figure 5 that the angular velocity of the mechanical arm gradually decreases during the opening process of the cleaning robot. Figure 6 shows that the maximum angular acceleration of the mechanical arm during the opening process of the cleaning robot is $\omega_1 = 0.00874 \text{rad} \cdot \text{s}^{-2}$. From the figure, it can be concluded that the change trend of the calculated value is consistent with the simulation result. The angular velocity of the mechanical arm has little change and is getting slower and slower, which better realizes the control of the final position. The whole movement process is stable and meets the design requirements.
It can be seen from Figure 7 that the maximum thrust of the cylinder $F=14492.961\text{N}$ during the opening process of the cleaning robot. From the figure, it can be concluded that the change trend of the calculated value is consistent with the simulation result, which provides favorable parameters for the selection of the cylinder.

The simulation data is processed to obtain the deviation graph of the angular velocity and angular acceleration of the manipulator arm as shown in Figure 8 and the deviation graph of the cylinder thrust as the time variation shown in Figure 9.

![Deviation graph of the angular velocity and angular acceleration of the manipulator arm](image1)

Figure 8 Deviation graph of the angular velocity and angular acceleration of the manipulator arm

![Deviation graph of the cylinder thrust as the time variation](image2)

Figure 9 Deviation graph of the cylinder thrust as the time variation

It can be seen from Figure 8 that the maximum deviation between the simulated and calculated values of the angular velocity and angular acceleration of the mechanical arm during the entire movement does not exceed 3.1%, and Figure 9 shows that the maximum deviation between the simulated and calculated values of the cylinder thrust does not exceed 4.99%. The maximum deviation between the simulation results and the calculation results does not exceed 5%, and the deviation is within a reasonable range. The simulation results verify the correctness and reliability of the mathematical model, and provide a theoretical basis for the next control system design and strength analysis.

5. Conclusions
(1) Designed a silo cleaning robot to solve the current problems of manual cleaning construction and many safety accidents, and realize unmanned warehouse cleaning. And verify the feasibility of the scheme through experimental devices. This robot adopts an umbrella structure, which enters from the material inlet during construction and does not damage or modify the silo. In addition, the robots are installed section by section, which reduces the difficulty of construction and facilitates transportation before construction and storage of robots in later stages.
(2) Through mathematical modeling and simulation analysis, it is concluded that the whole movement process is stable and meets the design requirements. The maximum deviation between the simulation result and the calculation result does not exceed 5%, and the deviation is within a reasonable range, which verifies the correctness of the mathematical model. It provides a theoretical basis for the design and strength analysis of the control system of the silo cleaning robot, and lays a foundation for better automatic control of the robot.

(3) This silo cleaning robot solution can be extended to the cleaning construction of other silo-shaped storage silos such as coal bunkers, granaries and ore silos.

References
[1] WANG Weiheng, YAN Qing, ZHU Xu. (2016) Causes and Treatment Measures of Caking in Cement Silo. Cement Technology. 2: 88-89.
[2] ZHAN Jiayu, LI Wanmin, FANG Guiming, et al. (2021) Research on Flowability of Cement Powder and Its Adhesion with Different Wall Materials. Bulletin of the Chinese Ceramic Society. 40(02): 401-406.
[3] LI Senlin, XIE Tao, ZHONG Pengfei. (2018) Use Mechanical Cleaning to Eliminate Safety Risks. In: Proceedings of the Fifth Domestic and Foreign Cement Industry Safety Technology Exchange. Chongqing. pp. 86-88.
[4] ZHANG Jiulei. (2020) Kinematics Simulation Analysis of Six-legged Upright Walking Robot based on Adams[J]. Journal of Mechanical Transmission. 44(8): 147-152.
[5] LI Zheng. (2018) Design and Research on the Dynamic Characteristics and Control System of Hydraulic Vertical Shaft Drill. China University of Mining and Technology, BeiJing.
[6] ZHAN Diwei. (2015) SolidWorks2015 Mechanical Design Tutorial. China Machine Press, Beijing.
[7] CHEN Zhiwei, DONG Yueliang. (2012) MSC ADAMS Multibody Dynamics Simulation Foundation and Case Analysis. China Water and Power Press, Beijing.