

Research on Characteristics and Precision Injection Angle Control System of Micro Particles Blaster Cleaning for Stone Material Surface Pollutant

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Abstract. For analyzing the injection angle impact of micro particles blaster cleaning system, the numerical two-phase flow model of gas-solid is built according to the characteristics of cleaning system, and the injection processes are simulated for different injection angle and soft/hard grinding materials. The simulation results indicate that the injection angle contributes a great influence on average pressure and effective area of cleaning, especially for the soft grinding materials. And concerning the actual operation difficulties of injection angle adjustment, the system is optimized by adding an electrical servo system to control angle of nozzle, which can realize the precise and quick positioning of angle-dimension in the course of cleaning.

1 Introduction

The culture relic of stone material (including stone statue, inscription on stone tablet and precipice, Cave Temple etc.) is of great significance for China's historical and cultural heritages. The culture relic is corroded due to long exposure to natural weathering, organism and acid rain infection, so it has to be cleaned for protection. The micro particles blaster cleaning method is widely adopted, with the superiority of clearing the insoluble hard scale layer[1] and the pollutant cannot vaporize when heated, and no hazards both for the bodies and environment, compared with the laser or chemical methods[2, 3].

Compressed air is used as driving force in the method of micro particles blaster cleaning, and the air-particles mixture is jetted to the surface of stone relic, thus clearing the pollutant by the actions of impacting and grinding. The sketch map of the cleaning system is shown as Figure 1, including the supplement of compressed air, pressure regulation and dehumidification system, grinding materials control system and the nozzle location control system for horizontal and longitudinal.

The problem for this method is that the vertical injection cleaning cannot always be effective and moderate when cleaning the rugged surfaces or tridimensional shapes, which is caused by the different level of corrosion or the profile of the relics. The pollutant cannot be removed without enough cleaning force while the culture relic, which is rare and irreversible resource, will be damaged with too much cleaning force. So it is necessary to research the injection course of micro particles blasting cleaning, especially the effect of the injection angle to realize the precise cleaning.

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Meanwhile, the parameters of the particles cleaning process such as the best injection angle, shape of jet flow, average cleaning pressure and effective cleaning area, different types of particles have to be researched, which impact the cleaning effect dramatically.

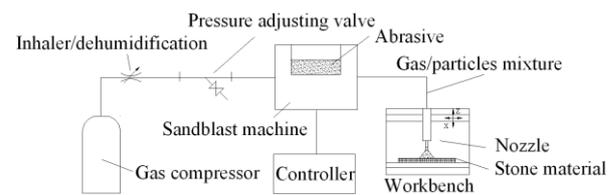


Figure 1. The sketch map of micro particles blaster cleaning system

Nowadays the injection nozzle location control system only could move towards the x-z plane, and cannot change the injection angle except the vertical one. So it cannot perform the multiple angles cleaning following the rugged position for best injection angle.

So the cleaning system is enhanced by high-accuracy electrical servo system, with increasing an angle DOF(degree of freedom) to control the injection angle of nozzle. The injection angle command is imported, which is followed by the output of angle control servo system to change the nozzle swaying angle. For meeting the design requirement of the precision angle control to nozzle, the variable structure control method and harmonic gear reducer are used in this electrical servo system to improve the angle control accuracy without return difference and overshoot, and then enough swaying speed and load capacity can be obtained as well.

2 Model descriptions and basic assumptions

According to the actual cleaning process, the physical model is built as Figure 2. Set the outlet zone of the nozzle as the mass inlet boundary condition, the cylinder as the far field to calculate the air-particle jet shape. The distance from injection inlet to the surface of stone material is called injection distance, α is the angle between nozzle and stone material. The structure of mechanics observation field is shown as Figure 3.

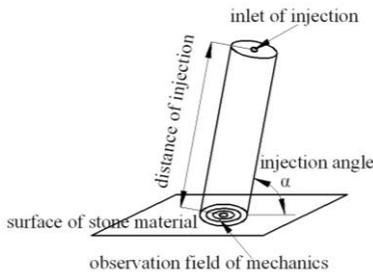


Figure 2 Computational model

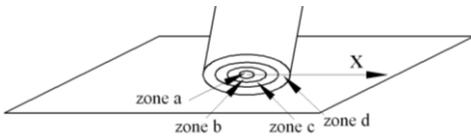


Figure 3 Structure of mechanics observation field

Firstly, the RNG $k-\epsilon$ is chosen as the turbulent equation. Then the injection condition of the compressed air is described by Euler method, and the Lagrange method traces the stream of the grinding particles, using the boundary condition of gas-particle inlet as mass flow rate. By mean of the coupling computations between two phases, the transform and action of momentum and energy can be accomplished both for continuity field and discrete field. At last every space point of flow distribution can be expressed.

The actual cleaning processes are complicated that in order to emphasize the crucial coefficient of injection and simplify the computation, some suppositions are made as follows:

- (1) The grinding materials are regular sphere particles, with homogeneous spray into the air flow.
- (2) The mode of particle impacting the surface of stone material is reflection.
- (3) Only considering the Basset acceleration force, pressure gradient force, thermophoretic force, Magnus force and Saffman lift, ignoring others.

3 Simulations and analysis

The kinds of grinding materials are divided into hard and soft according to their Mohs hardness whether harder or softer than silica sand. For the different characteristics of material, the glass beads (hard grinding material) and the walnut sand (soft grinding material) were selected as the typical materials. Working conditions were designed to simulate the different injection angles(15°interval), as

shown in Table 1, defining the distance of injection as 50mm, and the diameter of the particles as 300 μ m.

Table 1 Calculative conditions

No.	Injection angle $\alpha/(\circ)$	Material	No.	Injection angle $\alpha/(\circ)$	Material
1	90	walnut sand	7	90	glass beads
2	15	walnut sand	8	15	glass beads
3	30	walnut sand	9	30	glass beads
4	45	walnut sand	10	45	glass beads
5	60	walnut sand	11	60	glass beads
6	75	walnut sand	12	75	glass beads

The trace stream comparison of the walnut sand and glass beads are shown as Figure 4. They can indicate that the stream lines of walnut sand look loose because of the lower density, but the distribution of the stream lines is mainly regular due to the compressed jet flow with high speed and pressure. Meanwhile, the distribution formed of glass beads is more regular to follow the jet flow.



(a) Walnut sand



(b) Glass beads

Figure 4 Stream lines of particles

As shown in Figure 5, the average pressure varies dramatically with different injection angles. The simulation results indicate that for the walnut sand of the designed conditions, the zones suffer the highest pressure with the injection angle 15°, and the lowest with 90°, and the mainly difference exists in the center zone a. While the angle is 15°, the pressure gradient is large, which means the effective cleaning area becomes smaller. In addition, with the reduction of the angle, the gravity of the particles affects the stream line, which increases the difficulty in precise positioning.

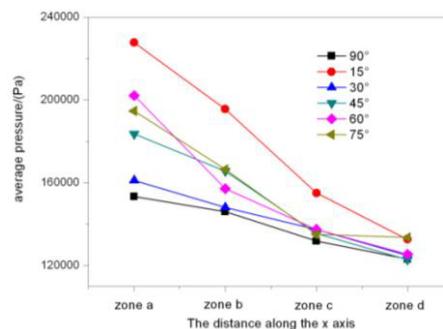


Figure 5 Average pressure comparison(walnut sand)

As shown in Figure 6, for glass beads, the best cleaning effect occurs when the injection angle becomes 90°. Compared with the walnut sand ones, the pressure variation relative to different injection angles of the same observation zone is lower which means less sensitive to the change of injection angle. Nevertheless, different injection angles can also bring much effect on the cleaning area.

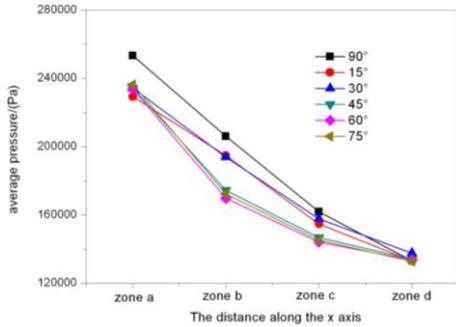


Figure 6 Average pressure comparison(glass beads)

4 Precision injection angle Control system

Both simulation results show that the injection angle affects the cleaning performance dramatically, especially for the soft grinding materials. For relics which consist of many three-dimensional surfaces, such as the statues, the cleaning system nowadays can simply realize the nozzle movement along the x - z plane without the function of swaying multiple injection angles according to the relic profile, and the most urgent problem is how to adjust the injection angle precisely and quickly.

So the cleaning system is advanced by the high-accuracy electrical servo system, by increasing an angle DOF α , which can sway nozzle depending on the shape of the relic surfaces. The best injection angle can be determined according to different relic surfaces, grinding materials and the cleaning requirement and executed by this high-accuracy electrical servo system for swaying nozzle. So the servo system develops the dexterity of the cleaning system, and reduces the working time. The improved system is shown as Figure 7.

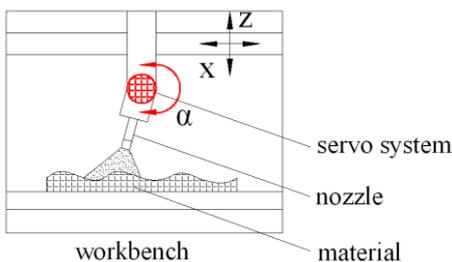


Figure 7 Improvement of the cleaning system

The nozzle swaying system is an angular servo system, including components of injection angle calculating unit, controller, power drive, servo motor, harmonic gear reducer and angle position sensor. First of all, the best injection angle α can be calculated by the

shape of relic surface, cleaning requirement and grinding materials. Then α is imported into the controller of servo system, which can receive the actual swaying angle α' measured by angle position sensor simultaneously, and according to the difference of α and α' , the control output u can be calculated by law of variable structure control. Afterwards u is amplified by the power module to drive the servo motor. The motor rotating speed is reduced by the harmonic gear reducer to form the actual swaying angle of nozzle. Thus the high-precision angular positioning has been achieved between the nozzle and the cleaning surface of relic.

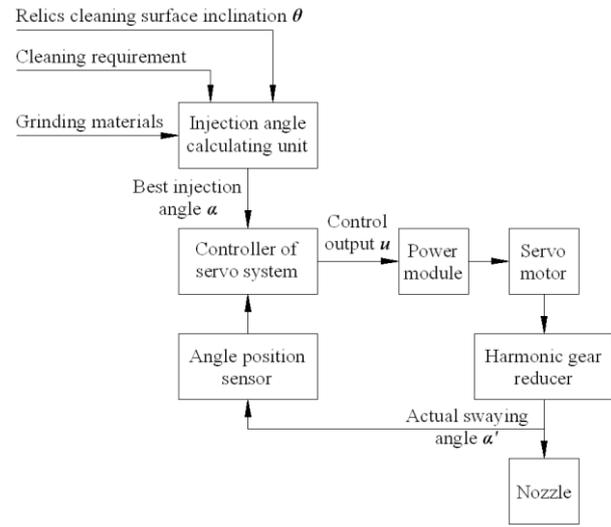


Figure 8 Electrical servo system for swaying injection angle

The controller of nozzle swaying system is designed by sliding mode variable structure control method. Choose the error signal e between the ideal swaying angle α and the actual one α' , and its first-order derivative \dot{e} as the state variables, which can be written as

$$\begin{aligned} x_1 &= \alpha - \alpha' = e \\ x_2 &= \dot{\alpha} - \dot{\alpha}' = \dot{e} \end{aligned} \quad (1)$$

Then the state space equation of the plant is written as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{\tau_m} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_m K}{\tau_m} \end{bmatrix} u \quad (2)$$

Where K_m and τ_m are the amplification coefficient and time constant of servo motor, and K is the transfer coefficient of harmonic gear reducer.

Then the sliding mode equation of the system is

$$s = cx_1 + x_2 = 0 \quad (3)$$

Where c is the coefficient of sliding mode.

By the sliding mode existence conditions of variable structure control system(reachability conditions)

$$s\dot{s} \leq 0 \quad (4)$$

Finally, the law of variable structure control system can be derived as follows,

$$u = \psi x_1, \quad \begin{cases} \psi_1 < k, & s > 0 \\ \psi_2 > k, & s < 0 \end{cases} \quad (5)$$

$$\text{Where } k = \frac{\tau_m c^2 - c}{K_m K}.$$

The angle of nozzle swaying system varies from 15° to 165° . Simulink curves and test results show that this system can follow the injection angle command very well, angular position accuracy is 0.2° without any overshoot in step response, and swaying speed can reach $240^\circ \cdot s^{-1}$ while enough load capacity can be provided.

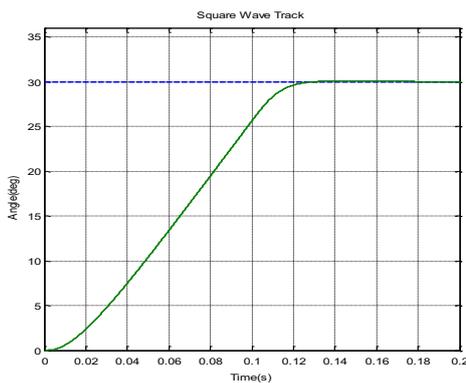


Figure 9 Simulation curve of step response

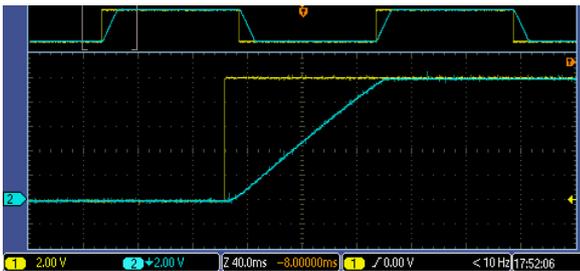


Figure 10 Test result of step response

5 Summary

The problems of injection characteristics for injection angle impact concerning soft/hard grinding materials and high accuracy control of injection angle were researched for micro particles blaster cleaning system. The numerical two-phase flow model of gas-solid has been built based on the characteristic of cleaning system. The cleaning processes of different injection angles and grinding materials are simulated. The cleaning system is improved according to the results of simulations, by adding an electrical servo system to control nozzle swaying which can realize the precise and quick positioning of injection angle. Conclusions can be summarized as follows:

(1) The numerical two-phase flow model of gas-solid can support the theory analysis for the research on micro particles blaster cleaning.

(2) The simulation results indicate that the average pressure and effective area of cleaning vary with the different injection angles significantly. For the actual cleaning, the cleaning effect of center and surrounded zones can be estimated by referring to the calculative values firstly, which can suggest the angle selection before cleaning.

(3) The precise swaying angle control of the nozzle was developed by applying an angular positioning servo system. The variable structure control method and harmonic gear reducer were used in the servo system to improve the angle control accuracy without return difference and overshoot. The maximum rotation angle is from 15° to 165° with the accuracy of 0.2° and $240^\circ \cdot s^{-1}$ swaying speed.

(4) The best cleaning results was obtained by precision control of injection angle. Three-dimensional precise injection positioning is accomplished including horizontal axis x , z and injection angle α , which can always keep the best injection angle according to the material surface. Meanwhile the theory and injection angle control system can be used in applications of micro particles blasting cleaning for other materials and surface shapes.

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