Design and Structure Simulation Analysis of Sand-mold Inkjet Printing Device

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Abstract: Ink-jet printing technology is a digital high-efficiency forming technology that can realize the rapid manufacturing of sand mold for foundry. This paper designs a low-cost, high-reliability ink-jet printing device based on the sand-mold inkjet printing process, and uses ANSYS finite element analysis software to carry out static analysis and modal analysis for its main frame. The analysis results show that the main frame has good rigidity and high strength, there will be no large deformation and resonance in frame under the working conditions, which can meet the requirements of sand-type inkjet printing devices.

1. Introduction
Sand mold inkjet printer is a sand mold rapid prototyping device developed based on three-dimensional printing technology[1]. The printer selectively sprays the adhesive on the sand layer of the premixed curing agent through the array nozzle, so the sand particles can be bonded and hardened; Stacking layers of materials to achieve additive manufacturing. Inkjet printing technology has the characteristics of good automation, high material utilization rate, and strong process flexibility, so it is widely used in patternless manufacturing[2,3]. It can shorten the development cycle of new products, improve efficiency, reduce costs, and improve accuracy.

Based on the application research of sand mold additive manufacturing, this paper develops the design of printing device suitable for sand mold forming, and carries out the finite element analysis of the corresponding main structure. Develop low-cost, high-reliability sand printing devices, laying the hardware foundation for powder printing technology research.

2. Printer structure design
The schematic diagram of the sand-mold inkjet printing device designed in this paper is shown in Fig 1. In the pre-processing, we should discretize the three-dimensional model into a series of continuous sheets with controllable thickness in the computer, and then use computer generate the contours of each layer of the sheet as the bitmap file which can be recognized by the nozzle program, finally import the bitmap into the printer control system; In actual printing, the bottom plate of the forming cavity is lowered by a layer thickness, then the sand paving device moves from the top of the molding chamber
while shaking off a certain amount of sand, and the shaken off sand will be leveled by a scraper; then the control system drives the print head to spray adhesive selectively to cure the sand mold according to the data information of each layer. The unbound sand will support the sand mold structure. After the single-layer printing is completed, repeat the above sand removal and adhesive spraying process until the model printing is completed.

![Fig 1 The schematic diagram of the sand-mold inkjet printing device](image1.png)

The maximum forming range of the sand type inkjet printing device designed in this paper is 320mm×400mm×200mm. The three-dimensional structure design of the device is shown in Fig 2. It mainly includes three modules: the injection system, powder spreading system and the mechanical structure.

![Fig 2 The three-dimensional model of the device](image2.png)

1) The injection system: Used to form adhesive droplets, spray the adhesive solution onto the surface of the sand powder in an array according to the bitmap setting, and bond layer by layer to form an entity. Considering the cost, forming accuracy and efficiency, the SUREjet-W160 industrial-grade thermal
foaming nozzle developed by Suzhou Ruifa Company was selected, and a negative pressure ink supply system was designed to connect the ink cartridge to achieve continuous supply of adhesive solution.

2) Powder spreading system: This system spreads the sand particles to be formed into a flat thin layer and scrapes it through the movement of the sand paving device. The flatness and density of the laid sand layer will directly affect the quality of the formed part.

3) Mechanical structure: As a small ink-jet printing platform, the main frame design should consider the stiffness, stability and durability of the load, therefore, this device uses stainless steel and high strength aluminum alloy as mechanical structure materials.

3. Structure analysis theory
According to the theoretical knowledge of classical mechanics, the dynamic equation of the dynamics of general structure objects is as follows[4,5]:

\[ [M]\dddot{x} + [C]\dot{x} + [K]x = F(t) \]  

(1)

Among them, \([M]\) is the mass matrix of the structure object, \([C]\) is the damping matrix of the structure object, \([K]\) is the stiffness matrix of the object, \([F(t)]\) is the force vector of the object, where \(\dddot{x}, \dot{x}, x\) are the acceleration vector, velocity vector and displacement vector of the structure object, respectively. Under normal circumstances, when the system structure model is under static conditions, the inertia and damping of the structure can be ignored. Approximately, the system model can be considered to be in a balanced state. At this time, the mass of the object can be ignored and the structure will not be affected. Reasonable constraints should be given to the constraints of the structure itself. At this time, the quantity related to time \(t\) in the kinetic equation is also ignored. The equations of the structural mechanics of objects can be simplified as:

\[ [K]x = F \]  

(2)

At this time, the response of the structural object can be simplified as a linear problem about the force vector of the stiffness \([K]\) and the displacement deformation vector.

In the analysis of dynamic mechanics, modal analysis is the basis of structural dynamics analysis and has a wide range of practical significance. It can help designers estimate the analysis parameters of the system model under dynamic conditions and predict the vibration form of the system structure at different frequencies. So as to avoid the occurrence of resonance phenomenon in the design, and improve the reliability of the designed product. In modal analysis, the damping coefficient in the dynamic equation is zero, and the vector force acting on time is also zero. At this time, the dynamic equation can be regarded as the solution of a typical undamped eigenvalue problem. The equation can be described as equation(3); Then simultaneous equations of the simple harmonic vibration, we can gain equation(4); solve the equation, the natural frequencies of modal analysis can be obtained as equation(5)

\[ [M]\dddot{x} + [K]x = 0 \]  

(3)

\[ ([K] - \omega^2[M])x = 0 \]  

(4)

\[ f = \frac{\sqrt{[K]/[M]}}{2\pi} \]  

(5)

4. Finite element analysis
The main frame bears all the loads of the three-dimensional motion module and other auxiliary devices during the working process of the sand-type inkjet printer, so its strength and rigidity affect the stability and reliability of the entire device. In order to avoid the impact of body deformation on the forming accuracy, and to understand the natural frequency of the frame to ensure a stable structure and normal operation, it is a must to carry on the static stress analysis and modal analysis to the host frame. ANSYS
is the most widely used finite element method numerical calculation software in the engineering field, the finite element analysis method based on ANSYS can accurately reveal the force and deformation of the device host structure and find out the unstable factors that may exist on the printer structure[6].

4.1 Geometric model simplification
According to the needs of finite element calculation, the structure of the inkjet printing device is simplified, the main frame is retained, and non-load-bearing parts such as lead screws, guide rails and rollers are removed, and the equivalent load is applied to the corresponding parts of the frame. In order to improve the calculation efficiency under the premise of ensuring the calculation accuracy, the transition fillets and threaded holes are ignored. The simplified three-dimensional model of the frame structure is shown in Fig3(a), and the design of the sand lifting mechanism is shown in Fig 3(b).

Fig 3 Three-dimensional model of frame structure(a) and lifting structure(b)

4.2 Material parameter assignment
The main frame, moving platform, forming cavity wall are defined as aluminum alloy material, elastic modulus $E= 71\text{GPa}$, Poisson's ratio $\mu=0.33$, density $\rho=2770\text{kg/m}^3$, yield strength $280\text{MPa}$; The lead screw, lead screw nut, smooth screw are set as stainless steel materials, the elastic modulus $E= 200\text{GPa}$, Poisson's ratio $\mu=0.3$, density $\rho=7850\text{kg/m}^3$, yield strength $250\text{MPa}$;

4.3 Finite element meshing
Import the established geometric model into ANSYS software for mesh division and verify the independence of the mesh. The grid independence verification results are shown in Table 1. The mesh size is controlled to ensure 3 to 4 layers of mesh on the minimum feature length, and local mesh refinement is performed on key parts (such as the connection between the support plate and the fixed plate). The final overall structure grid number is 195,448, and the grid division is shown in Fig 4.

| Element number | Element Quality | Maximum stress value (Mpa) |
|----------------|----------------|---------------------------|
| 49721          | 0.9582         | 23.579                    |
| 195448         | 0.9661         | 23.154                    |
| 423466         | 0.9554         | 23.591                    |
4.4 Boundary condition setting

The following boundary conditions are imposed on the finite element model according to the real working conditions:

1) Considering the overall quality of the motion system, print nozzle and other auxiliary devices, a surface load of 300N is applied to the upper surface of the sand box as equivalent load.

2) Considering the weight of the frame structure, impose gravitational boundary conditions on it.

3) Select the most extreme eccentric load condition of the forming platform, that is the molding chamber is fully loaded and the sand recovery box is fully loaded; So, a surface load of 1000N is applied to the surface of the forming pallet, and a surface load of 300N is applied to the installation surface of the sand recovery box as equivalent load.

4) Impose fixed constraints on the bottom screw holes.

4.5 Statics analysis

Based on ANSYS, the deformation distribution cloud diagram of the sand mold inkjet printing equipment is shown in Fig 6(a), the equivalent stress cloud map of that machine is shown in Fig 6(b). The maximum deformation is about 0.037mm, and the maximum deformation occurs at the edge of the middle lifting floor. This deformation is negligible compared to the use function. The maximum principal stress value of the main structure is 23.13Mpa. The position where the stress is larger is the fixed restraint position and the contact position of the screw nut with the middle lifting floor. The stresses at all points are far less than the allowable stress of material. It can be seen from the results of statics analysis that the main engine structure has greater rigidity and strength, which can ensure the accuracy and reliability of the system.
4.6 Modal analysis results

Modal analysis is mainly used to analyze the dynamic characteristics of mechanical structures. In actual engineering, machinery and equipment will be subject to mechanical interference from the outside world, such as noise interference and vibration interference. Through modal analysis, dynamic parameters such as the natural frequency and mode shape of the structure can be obtained, which provides a theoretical basis for avoiding resonance of the machine, and also pave the way for other dynamic analysis of the machinery[7].

Improving the vibration resistance of the main frame structure of inkjet printers is an important measure to ensure the development of high-quality and efficient printing of sand-type inkjet printers. Therefore, it is necessary to carry out modal analysis for the mechanical structure of inkjet printers to grasp its natural frequency and vibration shape. Based on the ANSYS workbench platform, this paper conducts a modal analysis of the designed sand-type inkjet printing equipment, and extracts the printer's 1 to 6 vibration modes. The natural frequencies of each order are shown in Table 1. The mode cloud diagram is shown in Figure 7.

| Mode number | Natural frequency | Critical speed (r/min) |
|-------------|------------------|-----------------------|
| 1           | 76.8             | 4608                  |
| 2           | 79.6             | 4776                  |
| 3           | 88.1             | 5286                  |
| 4           | 204.6            | 12276                 |
| 5           | 339.1            | 20346                 |
| 6           | 451.2            | 27096                 |
In this device, the main external excitation is the power source of the moving platform-stepper motor, which rated speed is just 1200r/min. It is much smaller than the critical speed of the device mode. Therefore, we can draw a conclusion that the reliability and anti-vibration performance of the frame structure can meet the requirements of use.

5. Conclusion
1) This paper designs a high stability, modular inkjet printing device that can realize low-cost and high-efficiency 3D printing of sand mold.
2) The static analysis results of the mainframe frame show that the frame has good rigidity and high strength; the maximum stress value under working conditions is 23.1Mpa, which is far less than the material's yield strength.
3) The modal analysis results of the mainframe frame show that the frame has good anti-vibration performance, and the natural frequency is greatly different from the excitation frequency, which can avoid resonance.

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