Study on the dynamic fatigue performance of shot blasting machine’s blades based on modal analysis

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Abstract. Shot blasting is an important means of metal surface treatment, and the fracture of rotating blade is the main reason for the abnormal operation of shot blasting machine. In order to prolong the service life of the equipment, the dynamic fatigue characteristics of the blade are studied in this paper. A three-dimensional model of the blade is established and its constraint modal are analyzed by both simulation and experiment. The results show that the deformation of blade is proportional with the increase of natural frequency, and the stress concentration is easy to occur at the root of blade. Meanwhile, the dynamic fatigue test of the blade is carried out, and it can be found that the root of the blade breaks at the rotational speed of 750r/min, which verifies the correctness of simulation results. Therefore, it is necessary to effectively adjust the control speed to ensure the normal rotation of the blades and reliable operation of the machine.

1. Introduction

Impeller head is the core part of shot blasting machine, including shot wheel, guide sleeve and blade installed on disc. When the projectile wheel rotates, the projectile will be driven out and moved to the blade through the directional sleeve [1]. High-speed rotating blades strike projectiles and push them to continue to rotate in the shot blasting machine. The projectiles will slide to end of the blade due to centrifugal force and finally reach the launch port. The projectiles strike the work piece surface at high speed. In this process, the working environment of blades become to worst. The blades constantly hit the projectiles from the pill wheel at high speed condition. The blades will bear the dynamic impact force of the projectiles and the center force of the disc during the work of the impeller head [2]. These forces change periodically, resulting to the resonance of the blade. The risk of blade breakage is extremely high. Once the blades break, the broken blades will hit the remaining blades violently to bring the damage of the shot blasting machine.

He [3] found that the blades were indented due to the impact of the projectiles. And micro-cracks formed around the indentation, which led to the failure of the blade. Liu [4] indicated that the impacted area was prone to form plastic deformation and lost plasticity under the action of stress concentration, when the projectiles impacted the blades repeatedly. Gao [5] pointed out that an incident angle, and the force of the projectiles on the blades could be decomposed into normal force and tangential force, when the projectiles acted on the blades. The blades surface could be cut and form microscopic chips when the projectiles rubbed against the blades. Ji [6] proposed that continuous impact was the major
influence to bring work hardening of the blade surface and the formation of cracks along the blade depth direction. And the cracks would extend to intersect each other, resulting in grinding.

In this paper, a finite element modal is established by taking the blades of the shot blasting machine. The modal analysis of constrained blades of the shot blasting machine are carried out. The various natural frequencies and their dynamic effects of the blades can be obtained. The stress concentration under coupling cooperation is studied, which is compared with the experimental results to verify the simulation correctness.

2. Modal analysis theory

Because of the influence of the directional sleeve, the blades can hit the projectiles in a fixed position, and projectiles are easy to thrown from the port. These shocks change is periodical, which is the major factor of causing vibration and resonance of the blades of the shot blasting machine. In the paper, modal analysis is used to determine the vibration characteristics of the work piece. The dynamic balance equation of structures in modal analysis is:

\[ [M]\ddot{x} + [C]\dot{x} + [K]x = \{f\} \]

Where, \([M]\) is the mass matrix, \([C]\) is the damping matrix, and \([K]\) is the stiffness matrix; the \(\{f\}\) is the force vector, \(\{x\}\) is the acceleration vector of the node, \(\{\dot{x}\}\) is the velocity vector of the node, and \(\{x\}\) is the displacement vector of the node.

When the structure is not subjected to external load, the free mode is mainly analyzed, firstly. The formula can be simplified as follows[7]:

\[ [M]\{\ddot{x}\} + [K]\{\dot{x}\} = 0 \]

Setting \(\{x\} = \phi \sin[\omega (t - t_0)]\), eq.2 is changed to a feature value equation:

\[ [K]\Phi = \omega^2[M]\Phi = \lambda[M]\Phi \]

Here, \(\omega\) is the natural frequency and \(\Phi\) is the modal shape. Considering the structural characteristics of the blade of shot blasting machine, it is necessary to analyzed the vibration characteristics of constrained mode with eq.1. In this way, when the shot blasting machine is working, the rotation speed can be adjusted according to the vibration modal to avoid resonance of the whole structure.

3. Constraint modal analysis

According to the blade structure of shot blasting machine, a three-dimensional modal of the blades is drawn using the Solidworks, as shown in Fig.1. The blade is made of white cast iron, and material parameters are as shown in the Tab.1. Considering the structural characteristics of the blade of shot blasting machine, it is necessary to analyze the vibration characteristics of constrained mode with equation of eq.1. In this way, when the shot blasting machine is working, the rotation speed can be adjusted according to the vibration modal to avoid resonance of the whole structure.

| Table 1. The material properties |
|----------------------------------|
| Materials | White cast iron |
| Density/ (t/mm³) | 7.5×10⁻⁹ |
| Yang's mod/Mpa | 100000 |
| Poisson's ratio | 0.21 |

Setting the approximate global size as 5, the tetrahedral cell shape is selected, and the element type is C3D10 (10-node quadric tetrahedron element), with 4596 elements. Fig. 2 shows the blade of the shot blasting machine with meshing.

Figure 1. Assembly modal of blade  Figure 2. A single blade modal with mesh

Considering the dynamic characteristics of the blade, a single blade is selected for finite element modal analysis. The natural characteristics of the blade are analyzed by constrained modal.

3.1. Frequency results
Fully considering the installation characteristics of the blade of shot blasting machine, the constraint modal is proposed for the vibration frequency characteristics of work piece in the working state. In actual structure, the blades are constrained according to the degree of freedom of the part. As displayed in Fig.1, the blade is positioned through dovetail groove, and is fixed on the disc by pressing block. So boundary conditions are applied in this two positions. The dovetail groove of the blade contacts the disc and the pressing block are fixed. The calculation results of frequencies are shown in Tab. 2.

| Order | Natural frequency/Hz | Maximum deformation/mm |
|-------|----------------------|------------------------|
| 1     | 741.3                | 0.781                  |
| 2     | 1200.0               | 1.073                  |
| 3     | 2720.8               | 0.889                  |
| 4     | 2746.9               | 0.692                  |
| 5     | 4156.9               | 1.081                  |
| 6     | 4463.9               | 1.339                  |

As shown in Tab. 2, the natural frequency of 1st modal of the constrained modal is 741.27 Hz. At the same time, the natural frequency will increase as the order increases. Although the increase is positive, the change of increase has nothing to do with the order. The increase from 3st modal to 4st modal is the smallest, with an increase of only 30 Hz. There is almost no correlation between the maximum deformation and order. The maximum deformation of each step varies greatly, and there is no obvious positive or negative characteristic. The disorder of the relation between the natural frequency and the maximum deformation of the constrained mode is great, which may be due to the variation fluctuations caused by the constrained boundary conditions.

3.2. Vibration modal of constraint modal
The effective mass of a certain direction of a certain modal is the square of the sum of the product of the mass of each particle and the coordinates of the particle in the corresponding direction in the modal. A modal has an effective mass in three directions. The effective mass is proportional to the amount of deformation. In other words, the proportion of the equivalent mass in each direction is proportional to the amount of deformation.

| Order | X-component | Y-component | Z-component |
|-------|-------------|-------------|-------------|
| 1     | 4.209×10^{-4} | 8.748×10^{-13} | 1.482×10^{-11} |
| 2     | 1.000×10^{-10}| 2.103×10^{-11}  | 5.027×10^{-11}  |
| 3     | 2.482×10^{-5} | 4.387×10^{-12}  | 7.696×10^{-7}   |
Among the equivalent masses of each order of X component, 1st modal accounts for the largest proportion, reaching 70.69%, followed by 6st modal, accounting for 20.7%. Among the equivalent masses of each order of Z component, 4st modal accounts for the largest proportion, reaching 99.99%. In summary, the orders with the greatest influence are the 1st, 4st, 5st, 6st modal. Fig. 3 shows the vibration modal of the constrained modals of 1st, 4st, 5st and 6st.

![Figure 3. Constrained modal vibration modal](image)

As can be seen from the vibration modal of the constrained modals, 1st modal is bending vibration, and the maximum deformation position is at the tip of the blade. The maximum deformation position of 4st modal is at the two corners of the blade tip. The maximum deformation position of 6st modal is also at the two corners of the blade tip, then at the low two corners of the blade. Therefore, the four angles of the blade are the positions of large deformation.

### 3.3. Dynamic stress of constraint modal

The blade deformation and stress concentration are obtained and the stress distribution nephogram of modal 1st, 4st, 5st and 6st are shown in Fig. 4.

![Figure 4. Modal stress nephogram](image)
According to the stress nephogram of each modal, stress concentration generally appears at the connection between the dovetail groove and the blade. This is because the connection of the dovetail groove is right angle, and the whole blade is fixed on the disc by the dovetail groove. Shape and force lead to stress concentration.

4. Experimental verification

4.1. Test materials
The blade is made of white cast iron composed of C, Si, Mn, S, P and Fe, and the content of each component is shown in Table 4. The relative content of C is high, so the white cast iron has a higher hardness, the hardness of white cast iron is as high as 500HB; Secondly, the high content is Si, Si can significantly improve the elastic limit of the material, so that the white cast iron has the toughness. Before the test installation, the blade should be treated with rust removal, oil removal and edge grinding.

Table 4. Main chemical compositions of white cast iron (Wt%)

|   | C   | Si  | Mn  | S   | P   |
|---|-----|-----|-----|-----|-----|
|   | 2.3 | 1.2 | 0.75| 0.12| 0.12|

4.2. Test equipment
The shot blasting machine is widely used in industry. The name of shot blasting machine was TAAVS380, as shown in Fig. 6. Cr-Mo alloy pellets with a diameter of 3mm were used for shot blasting machine. The speed of the shot blasting machine was 500r/min, 750r/min and 1000r/min. The running time of the equipment was 30 minutes.

The blade was embedded in the dovetail groove of the disc, and pressed against with a pressing block. The bolt under the pressing block passed through the bolt hole on the disc, and then was tightened with a nut. In this way, the blade was fixed on the disc through the threaded connection. The installation of a single blade was shown in Fig. 6.
4.3. Test results and analysis

4.4. After the shot blasting machine runed for 30 minutes, checked the status of the blade. The blade of the shot blasting machine is broken when the test speed is 750r/min. The equipment runs normally when the test speed is 500r/min and 1000r/min. The reason was that 750r/min was the natural frequency of the blade, and the blade generated resonance fracture, which was consistent with the simulation results.

![Image of blade and dovetail groove](image)

Figure 7. Individual blade installation

The test results showed that one side of the dovetail groove of the blade was fractured, as shown in Fig. 7, which was consistent with the stress concentration area in the simulation results. Therefore, the simulation results were in good agreement with the test results, which verified the accuracy of the simulation.

The simulation and test results provided the basis for optimizing the blade structure of shot blasting machine. Therefore, the service life of the shot blasting machine can be extended by changing the wedge Angle, controlling the speed of the shot blasting machine, lengthening the length of the dovetail groove or adding reinforcing rib.

5. Conclusions

1. The simulation results show that the deformation increases with the increase of frequency in constraint modal.
2. All orders’ formations are output in simulation software post-processing. By comparing the equivalent mass of each directional component, the natural frequency has a greater influence on deformation. The results show that the 1st, 4th, and 6th modals have a big impact influence on the deformation. The maximum deformation is found at the top corner of the blade.
3. The simulation results show that there is stress concentration at the root of the blade, which is consistent with the phenomenon of blade fracture at the root in the experiment, indicating that the simulation is correct. In addition, the simulation and test results show that the blade resonates at the speed of 750r/min, so the blade fracture can be effectively avoided and the service life of the equipment can be prolonged by controlling the speed within 750r/min.

Acknowledgments

This work was supported by Key Project of Natural Science Foundation of Shandong Province (ZR2020KE022), Shandong Province Major Innovation Project (2019JZZY010451), Jinan Research Leader Studio Project (2019GXRC054).

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