Dynamic design of grinding and polishing machine tool for blisk finishing

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Abstract. A virtual prototype was built in the dynamic design process of grinding and polishing machine tool for blisk. Through the analysis of multi-body dynamic of main structures changed to be flexible, column and beam had been found to be the weak link of the whole machine tool. Column and beam were optimized by changing the layout of plate to improve the low order natural frequency. The multi-objective optimization solutions of column were obtained through the genetic optimization algorithm in the FEA software. The sensitivity analysis was used to correct a set of optimized solution for the engineering. According to the optimization result, a new beam structure with inclined reinforcement plate is put forward. The first three order natural frequency of the optimized column increased by 11.9%, 18.2% and 2.8% respectively. The first three order natural frequency of the optimized beam increased by 45.3%, 8.23% and 17.8%. Analysis result of the whole machine tool show that the static and dynamic properties had improved significantly after optimization.

1. Introduction
Improving the ratio of driving force and gravity is the core mission of aviation engine design[1]. It is an important measure to improve the ratio of driving force and gravity by designing the aircraft engine fan, compressor, turbine to be blisk. The blisk has the characteristics of complex shape, narrow passages between the blades, thin blades, easy deformation and difficult material processing[2],which makes the processing of whole blisk very difficult[3]. Processing quality of blisk has a crucial impact on the overall performance of aviation engines.

Generally blisk machining use of CNC milling or electrochemical machining and then grinding and polishing. At present, the general manual grinding and polishing of technical workers to complete the blisk finishing, grinding and polishing process using a dedicated test model to plan the grinding and polishing allowance to assess the quality of grinding and polishing[4]. Manual grinding and polishing processing is inefficient, which has uneven margin and poor portability of detection model. Processing quality and efficiency of blisk has seriously hampered the development of China's aviation engine technology. For this reason we developed a special machine tool, including grinding and polishing processing and testing in one which has broad prospects for practical application.

In this paper, Dynamic design method based on virtual prototype has been used to design grinding and polishing machine tool for blisk finishing in the development process[5], through multi-body dynamics analysis[6-7] to identify the weak point in the machine tool and improve it through structural optimization. We complete the evaluation and improvement of the virtual prototype machine performance in the preliminary design stage, discovering deficiencies in machine design as soon as possible.
2. Multi flexible body dynamics simulation of grinding and polishing machine tool for blisk finishing

The dynamic simulation of multi flexible body is mainly used to identify the weak links in machine tools, so as to optimize the structure of machine tools. The finite element analysis software ANSYS and multi body dynamics analysis software ADMAS are used in the simulation of the flexible multi-body dynamics of the machine tool.

First, we establish a rigid multi-body dynamics model on ADAMS platform, and then replace the main structure beam, columns, bed, saddle and ram by flexible body generated by ANSYS respectively. Thus, the respective flexible multi-body dynamic model of the main structure in the machine tool is constructed. According to the actual working condition, the corresponding motion and load condition, the multi flexible body model can be simulated and analyzed. The specific process is shown in Figure 1.

2.1 Multi rigid body dynamics modeling of the grinding and polishing machine tool for blisk

As a special machine tool for blisk grinding and polishing, the machine tool has the function processing and testing. The machine tool is composed of a complex structure. Tool head is arranged on one side of the gantry which is composed of a beam and two columns. The tool head has three degrees of freedom, X, Z and A. A measuring tool head used to detect blisk is installed on the other side of the gantry. The measuring tool head and the tool head have the same degree of freedom. The working table to install blisk contains Y and C two degrees of freedom. The working table which contains two degrees of freedom and the tool head or the measuring tool head which contain three degrees of freedom cooperate with each other respectively, so as to integrate the processing and testing.

The virtual prototype model of the grinding and polishing machine tool for blisk is shown in Figure 2, and the multi rigid body dynamics model of machine tool added with related constraints and loads on ADAMS is shown in Figure 3.

Figure 1 Flow of multi flexible body dynamics simulation

Figure 2 Virtual prototype of grinding and polishing machine tool for blisk finishing
2.2 Multi flexible body dynamics modeling of grinding and polishing machine tool for blisk

Build flexible body model of main structure beam, column, bed, saddle and ram on the ANSYS platform. It is needed to create a mass point at the connecting position between the structure parts and the external system in the generation process of the flexible body, which is also known as the interface point[8]. After meshing, through the ANSYS data interface output the intermediate format file of flexible body, then import into ADAMS and replace the rigid body parts. The multi flexible body dynamics model is established after the main structures are transformed into flexible bodies respectively. The parameters information of the flexible body of the main structural parts is shown in Table 1.

Add motion and load in the flexible multi-body dynamic model whose main structures are transformed into flexible bodies respectively. Measure deformation values in X, Y and Z directions with measuring tool established in the appropriate model during the simulation in order to assess the impact of the various structural parts on machine performance. The movement and load are defined as: working table linear movement velocity in all Y, Z and X directions are 100*SIN (2.5*Time) mm/s, C-axis rotary speed is 11.1r/min. Add the corresponding grinding and polishing force in the opposite direction of relative motion between grinding and polishing tools and workbench. The grinding force value is set as follows: \( F_x = F_y = F_z = 100N \)

| Table 1. Main structure flexibility parameters |
|-----------------------------------------------|
| Beam | Column | Bed | Saddle | Ram |
| Nodes | 23950 | 12390 | 42681 | 28016 | 14661 |
| Units | 10597 | 6502 | 20478 | 15501 | 7626 |
| Interface Points | 16 | 8 | 20 | 12 | 8 |

2.3 Analysis of simulation results of multi flexible body dynamics

The influence of a single structure on the accuracy of the machine tool is obtained by simulating the multi flexible body dynamics simulation of the machine tool. The influence of each structure in the X, Z and Y directions on the machine tool accuracy are shown respectively in Figure 4 to Figure 6. Abscissas in the figure are expressed as: 1-beam, 2-column, 3-bed, 4-saddle, and 5-ram.

![Figure 4 Contrast of X-axis deformation](image-url)
Figure 4 shows that the greatest impact on the accuracy of the machine tool in the X direction is column, followed by beam and ram, saddle and bed have minimal impact. Figure 5 shows that the greatest impact on the accuracy of the machine tool in the Y direction is column; saddle and bed have minimal impact. Compared with the beam, the ram has a greater impact. Figure 6 shows that the greatest impact on the accuracy of the machine tool in the Z direction is beam, followed by column and ram, saddle and bed have minimal impact. In summary, column and beam are the weak link of the whole machine tool, which have the greatest impact on the accuracy of the whole machine tool.

3. Optimization design of the structure of the grinding and polishing machine for blisk

According to the results of the simulation analysis of the multi flexible body dynamics of the machine tool, the weak link columns and beam of machine tool was found out and optimized. Improving the low-order natural frequency of the weak link is the optimization objective in structural optimization design. By changing the layout of plate to improve the low-order natural frequency of column and beam to improve dynamic performance of the machine tool.

3.1 Column optimization

When optimizing the column, the multi objective optimization of the column is exercised by using the structural optimization module in ANSYS Workbench. The multi-objective genetic algorithm is used to obtain Pareto[9] multi-objective optimization solution. Select a set of optimal solution from the Pareto solution set to meet the target requirements. The optimized solution is modified through sensitivity analysis, so as to be applied to engineering practice. Sensitivity analysis can be drawn rate of change of the static and dynamic characteristic parameters of the column for each design variables, so that the parameters can be modified more effectively.

Table 2 lists the optimization size of column after engineering amended.

| Design variables       | Original Size | Optimization of design parameters | Rounding size |
|------------------------|---------------|-----------------------------------|--------------|
| Wall thickness P1      | 20            | 23.043                            | 25           |
| Rib spacing P2         | 341           | 354.9914                          | 324          |
| Rib thickness P3       | 18            | 17.069                            | 18           |
| Rib spacing P4         | 217           | 173.77                            | 174          |
| Rib thickness P5       | 18            | 17.448                            | 18           |
| Rib spacing P6         | -341          | -342.72                           | -342         |
| Rib thickness P7       | 18            | 18.207                            | 18           |
| Longitudinal rib thickness P8 | 18     | 20.068                            | 20           |
Longitudinal rib thickness \(P9\) | 18 | 20.068 | 20
---|---|---|---
Longitudinal rib thickness \(P10\) | 18 | 20.068 | 20
Outer rib length \(P17\) | 80 | 98.4 | 100
Outer rib spacing \(P18\) | -30 | -12.33 | 0
Outer rib height \(P19\) | 400 | 558.4 | 560
Outer rib thickness \(P20\) | 40 | 59.40192 | 60

| Target | First order natural frequency | 154.69 | 172.51 | 173.23 |
|---|---|---|---|---|
| Second order natural frequency | 245.24 | 288.68 | 289.97 |
| Third order natural frequency | 454.68 | 466.28 | 467.68 |
| Stress (MPa) | 0.639 | 0.37 | 0.24 |
| Deform (\(\mu\)m) | 0.81 | 0.52 | 0.43 |
| Mass (kg) | 423.29 | 498.74 | 509.215 |

Comparative results are listed in Table 2 before and after optimization of the column parameters. We can know that the dynamic characteristics of the column after optimization are improved, where the first three order natural frequency of the optimized column increased by 11.9%, 18.2% and 2.8% respectively.

### 3.2 Beam optimization

After topology optimization, model of beam can be simplified as shown in Figure 7. The stress of the beam is complex and it need to take the influence of the gravity and the working load at rolling guide of the beam into consideration in the ANSYS Workbench environment. The optimization objective was set to 70%. The optimization results are shown in Figure 20 from which we can know that the orange part of the picture is the material that needs to be removed, and the gray part of the picture is the material that needs to be retained after optimization.

![Figure 7. Topology optimization of beam](image)

Table 3. Natural frequency contrast of beam before and after optimization

| | Second order natural frequency | Third order natural frequency | Forth order natural frequency |
|---|---|---|---|
| Optimization model | 446.42 | 583.39 | 695.84 |
| Original model | 412.45 | 495.29 | 628.55 |
| Increase or decrease in value | Increase 8.23% | Increase 17.8% | Increase 10.7% |

The first four order natural frequencies of the optimized model are obtained by the modal analysis of the beam optimization model. Table 3 lists the natural frequency values of the beam before and after the optimization. Compared with the original beam model, the first four natural frequencies were significantly improved. The first order natural frequency of the optimized model is improved by 45.3%.
4. Checking optimized grinding and polishing machine tool for blisk

The static analysis of the optimization model of the machine tool is shown in Figure 8. In the place where the grinding and polishing tool is installed, static load of 100N are added in X, Y, and Z directions respectively. Add fixed constraint at the bottom of bed. After finite element analysis, the static deformations in X, Y, and Z directions are obtained respectively, and shown in Figure 9 to Figure 11 respectively. The static deformations and static stiffness in X, Y, and Z directions of the place where the grinding and polishing tool is installed are calculated after the static load added. Table 4 lists the comparison results of static stiffness before and after optimization. Compared with the original model of the machine tool, the static stiffness of the optimized model in three directions was improved to different degrees. The static stiffness in X, Y, and Z directions increased by 7.32%, 62.3% and 340% respectively.

Table 4. Static stiffness contrast of machine tool before and after optimization

|                | X axis 100N | Y axis 100N | Z axis 100N |
|----------------|-------------|-------------|-------------|
| Deformation (μm) | Static stiffness (N/μm) | Deformation (μm) | Static stiffness (N/μm) | Deformation (μm) | Static stiffness (N/μm) |
| Original model | 0.88 | 113.636 | 1.25 | 80 | 0.66 | 151.515 |
| Optimization model | 0.82 | 121.95 | 0.77 | 129.87 | 0.15 | 666.66 |
| Stiffness increase | Increase by 7.32% | Increase by 62.3% | Increase by 340% |

5. Conclusions

In view of the technical problems such as manual grinding, separation between processing and testing of the blisk, we develop one special machine tool for blisk finishing, including grinding and polishing processing and testing in one.

In the development process of the machine tool, from the perspective of the system we use multi-body dynamics simulation to identify that column, beam are the weak links in the machine tool.

In order to improve the low order natural frequency of the weak links, beam and column are optimized by changing the layout of the ribs.

In the optimization process of column, sensitivity analysis is used to modify the engineering parameters for multi-objective optimization solution. According to the results of topology optimization, a new type of beam structure with internal diagonal ribs is put forward in the optimization process of beam. After optimization, the low order natural frequency of the column and beam structure is obviously
improved.

The static and dynamic characteristics analysis results show that the design method can improve the performance of machine tools.

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