Performance Improvement of a Vertical Shell Spinning Machine

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Abstract — A vertical shell spinning machine vibrates more under certain conditions resulting in low processing efficiency and poor spinning quality. In this paper we report on a software collaborative simulation environment of SolidWorks and ANSYS Workbench to investigate the static and dynamic analysis of the bed structure. The results showed that the effect of the spinning forces on the bed structure gives rise to distributed deformation and low-order natural frequencies and modes. The bed structure was improved so the low-order natural frequency is increased, avoiding resonance during the forming process. The control system was also improved. Combining spinning parameters detection, the key region of the operating curve predicted that the curvature of contour curve change greatly and can easily lead to critical defects. The control system was adjusted to reduce spindle and roller feed rate. Finally, the improved control system and improved bed structure were verified by experiments. Test results show that the performance of spinning machine has been significantly improved to meet the shell spinning high-efficiency and high-quality needs.

Keywords - Spinning machine; Bed structure; Stress; Modal analysis

I. INTRODUCTION

Spinning is a continuous local plastic deformation process, and is widely used in the field of aviation, aerospace, weapons and other metal precision machining since it has many outstanding advantages such as small forces of process transformation, save the raw materials, high production efficiency, good product quality, easy to realize lightweight and flexibility of the products[1, 2].

The self-designed vertical shell spinning machine was developed. The working steps show as fellows: the metal plate blank or prefabricated blank is clamped on the core mold of spinning machine, the core mold and blank material are rotated by the spindle shaft driven, rollers are used to exert pressure on the blank material, generate a continuous, pointwise plastic deformation to obtain the multi-standard contour shape hollow rotating housing. This spinning machine has some advantages such as good economics, simple equipment, easy handling, and good flexibility. However, with the increase in demand for products, the efficiency of spinning needs to improved. Through the analysis of spinning process parameters such as speed, feed ratio, reduction in pass, radius of roller, motion track [3, 4], this paper puts forward a new process scheme, the vibration increased between roller and work pieces in the experiment, the formed shell has rough surface, thickness unfair, some defects appeared on zone of large curvature contour curve. It maybe has a connection with stiffness of bed structure and natural frequency by preliminary analysis. Firstly, this article proposed to put the bed structure of vertical spinning machine as the research object, using SolidWorks and ANSYS Workbench software for its static and dynamic analysis, and studying the structure improved. Secondly, this paper also improved the control system, by prejudged the region of spinning defect critical sections, dynamically adjusted the spinning parameters (spindle speed and roller feed rate) to avoid the spinning defects. In other words, decreased the speed of spindle and roller feed rate on place where there have the large curvature change on contour curve. Combined with experimental verification, we are dedicated to find an effective way to improve production efficiency and product quality of the spinning machine.

II. FINITE ELEMENT MODEL OF BED STRUCTURE

The basic structure layout of vertical shell spinning machine is shown in Figure 1, which mainly consists of bed structure, spindle and core mold, feed mechanism of XZ direction, the roller cell, the presser foot assembly and electrical components and other components. The bed structure as a support base of the whole device, which accounts for a large proportion of the entire weight of the machine, and it is also the body of other components to fixed and motion. Therefore, the strength, stiffness and natural frequency of the bed structure will directly affects the entire mechanical properties of the spinning machine. Figure 2 shows the pressure distribution zone on upper surface of bed structure; specific loads are shown in Table 1, the value is equivalent value.
A. The establishment of 3D model

The bed structure of spinning machine is a whole plate girder welded structure, the beams, stringers and vertical beams are made of rectangular section steel; the upper and lower surfaces of bed structure welded steel; there are six rectangular plates at the feet of the bed structure. In order to ensure the analysis accuracy of the finite element, using Solidworks to make 3D solid modeling according to the practical engineering drawing of the bed structure. At the same time, taking into account the cost and cycle of solving, some features of the model such as small chamfer, small fillets, and screw holes has been simplified, and ignored the impact of welding stress and weld quality of the welding area.

B. Model meshed

By Solidworks to seamlessly connection to start ANSYS Workbench software, and introduced solid model built by Solidworks into the ANSYS Workbench for correlation analysis [5-6]. The material of bed structure is Q235, the material properties set in the software: the elastic modulus is 2.0×10^5 MPa, the Poisson ratio is 0.30, the density is 7850 kg·m\(^{-3}\), bulk modulus is 1.6667×10\(^{11}\) and shear modulus is 7.692×10\(^{10}\). Based on the modeling characteristics and mechanics features of the bed structure, the free mesh is applied. The finite element mesh model of bed structure is shown in Figure 3.

C. Boundary conditions applied

The bed structure fixedly connected to the ground via ground screw, six freedom degrees of each foot margin of the bed bottom surface are constraints, so the moving pairs and revolute pairs of the model are constrained along the X, Y and Z axis. Considering the bed structure surface is connected with a number of parts, with reference to Figure 2 and Table 1, the load is applied in the corresponding region, particularly as shown in Figure 4.
III. STATIC AND DYNAMIC CHARACTERISTICS ANALYSIS OF BED STRUCTURE

A. Static characteristics of the original bed structure

In the conditions of applied load, the maximum equivalent stress of the bed structure appeared in the spindle, the core model and the spindle motor; secondly, swing pressure mechanism and the bed structure connection region also exist a large stress, the two values are much closed. But the equivalent stress value of bed structure contact region is much larger compared to the previous two in terms of the XZ direction feed mechanism. This shows that, although the greatest stress appears in the latter region, but at the bottom there are beamed support the bed structure, which directly reduces its equivalent stress. From the results of analysis, the maximum equivalent stress of bed structure is 42.146 MPa, the value is much smaller compared to the allowable stress of Q235 material, the maximum deformation is 0.21 mm, and they are all located in region of spindle of upper surface of the bed structure. The maximum change of relative position of the knob and core model is 0.10 mm, which meets the accuracy requirements of the vertical housing spinning machine. Therefore, the structure of bed structure meets the design requirements in the static loading conditions.

B. Modal analysis of original bed structure

In modal analysis of bed structure, the setting of the material properties and the boundary conditions are the same as the static analysis. In the dynamic analysis of the structure, the dynamic characteristics of lower modal determined the dynamic performance of the entire structure, which is mainly manifested that the low-end frequencies are more easily coupled with external excitation conditions. So the impact is serious caused by the lower vibration modes of structure than the higher modes [7]. Therefore, only the first four order dynamic characteristics of bed structure were analyzed. Table 2 described the natural frequency and vibration mode of first four order of the bed structure.

As apparent from Table 2, the lower natural frequency of the bed structure is first-order and second-order; their values were 47.22 Hz and 53.54 Hz, respectively. However, in this paper the rated speed of the spindle drive motor of self-developed vertical housing spinning machine is 1440 r/min, servo motor rated speed of precession mechanism is 2000 r/min, the limit speed is 3000r/min; thus it can be determined that the self-excited oscillation frequency \( f = n/60 \) Hz which caused by own incentive of the bed structure. So the largest outside self-excited vibration frequency is 50 Hz, and close to first and second order natural frequency. Thus, the resonance condition will be occurred when the spinning formation. From the practical course, the 6061 aluminum alloy shell molding of 1 mm thick can be made when the speed of spindle is 600 r/min, and the surface roughness is low and the thickness is uniform. However, the machine vibration becomes larger when speed is increased to 1000 r/min, and the formed shell has a rough surface, uneven thickness, even obvious “spin crack” defect appeared in the bus-shaped curvature smaller place. Table 2 also shows that: when the frequency of the bed structure is the first-order and second-order, the stiffness of the spinning machine is insufficient in X and Y directions, so the stiffness of pillar is insufficient; when in the third-order, the bending stiffness in the spinning area of bed structure work surface is weak along the Z-direction; when in the four-order, torsional rigidity on the bed structure work surface is not enough along the Z-direction. Therefore, in order to increase the stiffness of the structure and stability of the bed structure, the bed base frame structure and layout should be changed.

C. The analysis bed structure improvement scheme

The sectional shape of structural component and the ribs layout of bed structure usually have a significant impact on mechanical properties [8]. On the premise of the machine does not change the overall installation dimensions, ensure that the internal space is reasonable. This paper presents two kinds of improved scheme of adding profiles or plates based on the original structure of the bed structure. The improved models after adding profiles are shown in Figure 5. The Figure 5(1) represents improved first scheme: in the horizontal direction of the bed structure increased six profiles. The Figure 5(2) represents improved second scheme: in the corresponding diagonal of the bed structure increased six profiles. The two improved schemes also put thickness of steel plates of upper surface of the bed structure increases 5 mm. After the re-calculate statics, the static maximum equivalent stress and deformation region are consistent with...
the original model, the specific values compare with each other as shown in Figure 6. The maximum value is 24.411 MPa in improvement first scheme, and reduced 42.1% than before, causing deformation between the knob and the mandrel is 0.08 mm. The maximum value is 23.317 MPa in improvement program one, and reduced 44.7% than before, causing deformation between the knob and the mandrel is 0.07 mm. So the both improved schemes can increase the spinning machine strength, but the second scheme is better.

After the dynamic characteristic analysis, the first four order natural frequencies and vibration mode of the two improved schemes are shown in Figure 7 and 8, respectively. The first four order natural frequencies of the original scheme and two improved schemes are shown in Figure 9. The first four order natural frequencies are significantly improved in improved first scheme, and the minimum first natural frequency value is 55.215 Hz. Although the value is higher than the machine's rated operating frequency 50 Hz, but there is still risk of resonance. The minimum first natural frequency value of the bed structure is 65.395 Hz in improved second scheme, the natural frequency of second order to fourth order were 74.253 Hz, 116.24 Hz and 120.65 Hz, and the fifth-order and sixth-order natural frequency reaches 125.33 Hz and 156.03 Hz. Therefore, when using the improved scheme two can avoid resonance in the spinning process, enable the device to play overall performance, improve the efficiency and quality of housing spinning molding.

The structure of bed structure has good stability in the improved second scheme, it not only in the static strength has been significantly improved, the first four order natural frequency also improved, the minimum first-order natural frequency is far higher than the working frequency of the vertical spinning machine, which can be avoided forming defects caused by resonance.
IV. SPEED ADJUSTMENT IN CONTROL SYSTEM

Through a large number of experiments, it is found that the spinning defects, especially the “spin split” points often appear in the region where the slope of the adjacent two section contour curve changes larger. Therefore, the attempt to use the control system in the slope changes in large area to achieve the reduction spinning, the slope changes small or no change is still high-speed spinning, so as to achieve the aim of preventing workpiece rupture and ensure machining efficiency. The change of the slope is judged by the spin path sequence generated by the spinning trajectory control model. When the slope of the contour curve of the workpiece is greater than a certain limit value $\Delta$ (the value of $\Delta$ can be obtained in advance by the spinning process experiments), the tool trajectory is adjusted in the range of the specified control range, so reduced speed of spinning formed. When the spinning trajectory sequence exceeds the specified control range, the high spinning speed will be restored. The roller trajectories workpiece shown in Figure 10, set the equation of the roller tool traveling contour trajectory curve is $z_i=f(x_i)$, the equation of paragraph $i$ is $z_i(x_i)$, and the starting point is $(x_{i1}, z_{i1})$, the ending point is $(x_{i2}, z_{i2})$. By the same token, the equation of paragraph $i+1$ is $z(i + 1)= f(x(i + 1))$ and the starting point is $(x(i + 1) 1, z(i + 1) 1)$, the ending point is $(x(i + 1) 2, z(i + 1) 2)$. Set spinning roller sequence is $j$ (in Figure. 10, $j=1,2,3, ...$), the roller order is $j$ when the slope change greater than $\Delta$, spinning was beginning range from $j(\Delta+S)$ to $j(\Delta+S)$, in that process $S=1,2,3, ......., $ the value of $S$ is adjusted according to the workpiece material and a maximum processing speed. Spinning deceleration start range from $j(\Delta-S)$ to $j(\Delta+S)$ when satisfy equation (1), if beyond the range, it recovery high-speed spinning.

Subroutine flowchart of spinning tracks having improved with speed adjustment (with red dashed box) is shown in Figure 11. In the figure, model of step13 can complete the above-mentioned calculation and judgment of speed adjustment, obtained the speed adjustment mark of each spinning trajectory, the speed adjustment mark of each spinning trajectory was added to model of step 14.
The original main system flowchart shown in Figure 12, in which the "trajectory control" (with red dashed box) is the improved control program module of spinning machine with a speed adjustment function.

Having improved control program flowchart with a speed adjustment function of spinning tracks shown in Figure 13 in which increased judgment of speed adjustment. So adjustment of speed can be control according to the speed adjustment mark in the model of step14 in Figure 10.

V. TEST PROCESSING VERIFIED

Spinning machine was machine dedicated system which can self-developed and automatically generate CNC spinning to go line track sequence. The system has good interpersonal interaction interface, spindle speed, feed ratio, pass reduction, spin the wheel radius, trajectory and other parameters can be entered directly; the system also has function of prevent spinning roller and the mandrel interference avoidance, before software judgment the interference which made by spinning roller and core mold, under spinning error allowed, re-planning the reasonable avoidance trajectory to ensure smooth completion of the spinning process. So, it also can avoid damage of equipment caused by collisions.

The design of the planned spinning process parameters and the contour trajectory curve slope variation limits V, deceleration spinning range S input into the control system of vertical housing spinning machine, spindle speed is 1000 r/min, the blank spin for pressure processing, the specific process shown in Figure 14: Figure 14 (a) for the spinning preparation stage, when the blank has been placed over the mandrel and the pressure put by the presser foot to its clamping mechanism. Figure 14 (b) and (c) are the main spinning stage, in the entire spinning process, the roller top-down movement of the workpiece along the outer edge of the normal gradually formed mandrel; Fig 14 (d) is the end spinning stage, After the completion of the last spinning, the roller return to the initial position. In the entire spinning process, the machine always work smoothly than before and base structure improvement vibration smaller thickness of the workpiece after spinning no significant heterogeneity,
and the surface is smooth, and uniform texture is clear, over the enter process, it is not occurred the "spin crack" and other serious defects. Namely by improving the base of the structure and improving the control system combining with the way that make the machine performance been fully tapped, thus spinning efficiency is also improved compared with the original program. The method can provide a reference for other similar machine equipment performance improvements, and it has theoretical and practical value.

(5) By the way of improving base of static and dynamic characteristics binding improving the control system combination, vertical spinning machine performance can be fully realized. This method can provide a valuable reference for other machine equipment performance improvements.

VI. CONCLUSIONS

(1) By using Solidworks design software and ANSYS Workbench finite element analysis software to build collaborative simulation environment, it can be carried out structural and modal analysis of vertical housing spinning machine frame. (2) By analysis the statics of the original structure, the results show that frame structure withstand the maximum equivalent stress is less than the allowable stress of bed material, deformation region meet the design accuracy of spinning machine. (3) The results of the original frame structure modal analysis show that first and second order natural frequency for frame is close to excitation frequency with the device of itself, and spinning machine work time is easily resonate. Putting forward the program of improving the base structure, its natural frequency simulation is solved by experimental verification, and can meet the performance upgrade requirements of vertical housing spinning machine. (4) When the change of workpiece outline trajectory curve slope greater than a certain limit, the spinning speed of spinning trajectory of the control range which appointed by this trajectory will deceleration, and it not only can be prevented from cracking of workpiece, but also to ensure processing efficiency.

REFERENCES