Research on Static and Dynamic Characteristics Analysis and Structural Optimization of Digital Turning and Milling Compound Forming Machine

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Abstract

This study focuses on the lightweight structural design of digital turning and milling compound forming machines. By selecting high-strength lightweight materials and optimizing the structural parameters of key components, the weight of the equipment is reduced while ensuring the strength and rigidity of the entire machine. Conduct static characteristic analysis on the vertical/horizontal turning and milling machine, establish the finite element model of the machine, and evaluate its stress, strain and displacement under static load. On this basis, modal analysis is carried out to clarify the configuration vibration characteristics and deformation laws under different modes, providing a basis for avoiding resonance. Applying the lightweight structure and analysis results to practice, this digital turning and milling compound forming machine has performed outstandingly in shortening the production cycle, improving processing accuracy and efficiency, promoting the development of the manufacturing industry towards intelligence and greenness, and has broad application prospects and practical value.

Keywords

Turning and Milling Compound Forming Machine; Lightweight Design; Structural Optimization; Static and Dynamic Characteristics; Modal Analysis.

1. Introduction

In the current wave of transformation of the manufacturing industry towards intelligence, greenness and high efficiency, digital turning and milling compound forming machines, as representatives of high-end manufacturing equipment, are playing an increasingly important role [1-3]. It integrates digital technology with the turning and milling compound processing technology [4-5], discards the cumbersome process of traditional mold manufacturing, and realizes the direct digital cutting and forming of processing objects such as sand molds. It not only significantly shortens the production cycle, but also significantly improves the processing accuracy and flexibility. However, with the intensification of market competition and the continuous improvement of requirements for equipment performance, how to achieve lightweight design of equipment while ensuring its functions and accuracy has become a key issue that the industry urgently needs to solve at present.

The turning and milling compound forming machine has been widely applied in high-end manufacturing fields such as aerospace, automotive manufacturing, and shipbuilding engineering due to its characteristics of high precision and high efficiency [6-7]. It can complete various processing tasks such as turning, milling and drilling on one device, reducing the process conversion time and improving the production efficiency and processing accuracy [8]. However, traditional turning and milling compound forming machines are often bulky in structure and have high energy consumption, which to some extent limits their application in certain fields where there are strict requirements for equipment weight and energy consumption [9-10]. Especially in the aerospace field, the

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lightweighting requirements for components are extremely high, and the lightweighting of the equipment itself has also become one of the key factors in enhancing the competitiveness of products.

However, the research and development as well as application of digital turning and milling compound forming machines have not been smooth sailing. How to achieve lightweight design of the equipment while ensuring processing accuracy and efficiency is a major challenge currently faced. Lightweight design not only helps to reduce the energy consumption and manufacturing costs of equipment, but also enhances its flexibility and adaptability, meeting the processing requirements in different scenarios. In addition, the application of digital technology has also brought new challenges. For instance, the optimization of the digital design process, the precise control of processing parameters, and the guarantee of equipment stability all require in-depth research and exploration.

In view of this, this study focuses on the static and dynamic characteristic analysis and structural optimization research of digital turning and milling compound forming machines[11-12], aiming to propose a set of practical and feasible design schemes for digital turning and milling compound moldless forming machines by combining digital technology, lightweight design concepts and advanced manufacturing processes. This scheme will fully consider key factors such as the processing accuracy, efficiency, lightweight and stability of the equipment. Through means such as optimizing structural parameters and improving manufacturing processes, the overall performance of the equipment will be enhanced[13-15]. Meanwhile, this research will also ensure the effectiveness and reliability of the designed scheme through experimental verification and performance evaluation, providing strong support for the promotion and application of digital turning and milling compound moldless forming machines.

2. Lightweight Design of Turning and Milling Compound Forming Machines

2.1 Design of Vertical/Horizontal Lightweight Mechanism Schemes

The design of the vertical/horizontal lightweight scheme for the digital turning and milling compound forming machine aims to achieve high efficiency, precision and lightweight of the equipment by optimizing the structure and adopting advanced digital technology. The vertical solution focuses on the utilization of vertical space, adopts a compact structural design to reduce floor space, and integrates a high-precision turning and milling compound processing unit to achieve multi-process integrated processing. The horizontal scheme emphasizes stability and processing flexibility in the horizontal direction. By optimizing the bed structure and guide rail layout, the rigidity of the equipment and processing accuracy are enhanced. Both adopt digital moldless forming technology to directly process materials such as sand molds, eliminating the mold manufacturing process and shortening the production cycle.

For the vertical solution, a compact structure design is adopted. Key components such as the bed are still made of high-strength materials to ensure stability and vibration resistance. The modular design facilitates production, maintenance and upgrading. The optimized tool layout enables quick switching between different processing requirements. Moreover, through the five-axis linkage technology, complex curved surface parts can be efficiently processed, as shown in Figure 1 (a). The horizontal scheme is characterized by a side-hung single column design, which has obvious advantages in torque output, load-bearing capacity and power. The double tool rest structure can simultaneously complete fine and rough machining, and is easy to operate. It ensures the smooth movement of the column and crossbeam while reducing weight and cost, as shown in Figure 1 (b).

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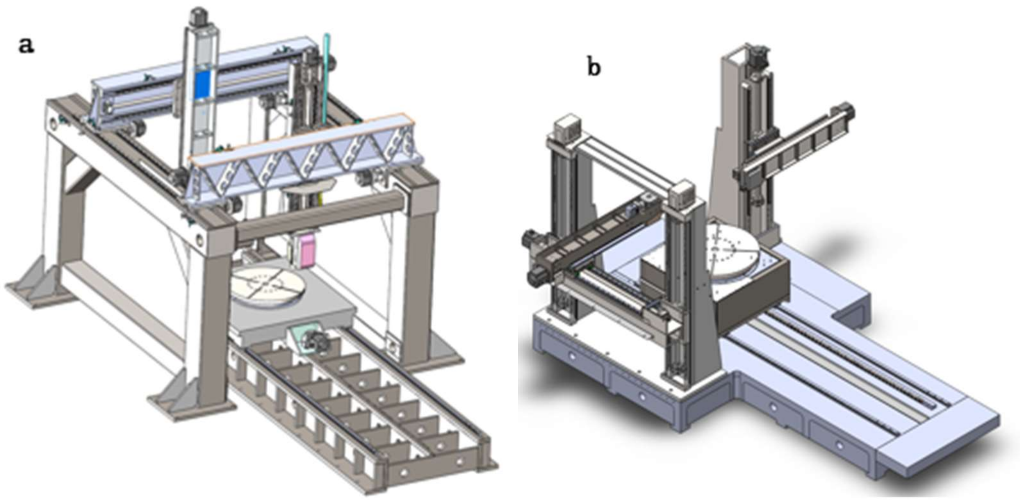

a)Vertical turning and milling compound forming equipment; b)Horizontal turning and milling compound forming equipment

Figure 1. Turning and milling composite lightweight design scheme

3. Static Performance Analysis

3.1 Structural Statics Theory

Statics analysis is a structural analysis method for studying static properties. The materials of the structure should meet the requirements of elastic materials and the theory of small deformation. Generally, the influence of inertia and damping is not considered. Through finite element statics analysis, it can be determined whether the usage conditions such as stiffness and strength are met[16-18].

The general equation of force balance can be obtained from the theory of classical mechanics:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \tag{1}$$

In the above formula:

$\{X\}$-- Displacement vector;

{F(t)}-- Force vector;

[M]-- Represents the mass matrix;

[C]-- Represents the damping matrix;

[K]-- Represents the stiffness coefficient matrix.

By dividing a whole into many similar small units, and establishing the equilibrium equation of forces for each unit, as shown in Equation (2) below:

$$[k]\{x\}=\{f\} \tag{2}$$

In the formula:

{x}-- Represents the degree of freedom on the unit node;

{f}-- Indicates the force acting on the unit node;

{x}And{f}-- All are vectors of 12×1;

[k]-- represents the magnitude of the force required for the deformation of each unit, which can be known from the above formula[k]It is a 12×12 matrix.

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Combining the equilibrium equations of all unit forces together, the overall equilibrium equation can be obtained, as shown in Equation (3) below:

$$[K]\{X\} = \{F(t)\} \tag{3}$$

In the formula:

[K]-- Represents the overall stiffness matrix;

{X}-- Represents the degrees of freedom on all unit nodes of the overall structure;

{F(t)}-- Indicates the external load acting on the node.

3.2 Analysis of Static Characteristics of Vertical Forming Machines

When the forming equipment is in operation, the motion axis usually undergoes a small amount of deformation, which will affect the processing accuracy of the forming equipment. Therefore, when designing the motion system, it is necessary to optimize the layout of the crossbeam reinforcing ribs and the cross-sectional guide rails. In order to ensure the lightweight design of the motion system structure, the finite element method is proposed for structural optimization.

By establishing geometric modeling for the Y-axis and Z-axis and making corresponding structural simplifications (ignoring transition fillets, threaded holes, and holes with a diameter less than 10mm, etc.). According to the requirements of the finite element simulation calculation, the Y/Z finite element model is established, and certain boundary conditions and loads are applied to the finite element model of the Y/Z axis. The applied factors include gravity, fixed constraints, acceleration, moment loads, etc. The boundary conditions and structural static calculation results of the milling shaft of the vertical digital moldless casting turning and milling compound forming machine are shown in Figures 2, 3 (a), and 3 (b). The structures of the equipment turning Y-beam and the milling Y-beam are the same. Since the milling shaft adopts a five-axis head, the stroke and height of the milling Z-beam are both greater than those of the turning Z-beam. Therefore, only the milling shaft is analyzed during the numerical simulation calculation. The simulation results show that under the loading condition of a force of 10kg, the maximum deformation of the vehicle structure is 0.17mm and the maximum principal stress is 1.5×10^{7}, which meets the strength requirements.

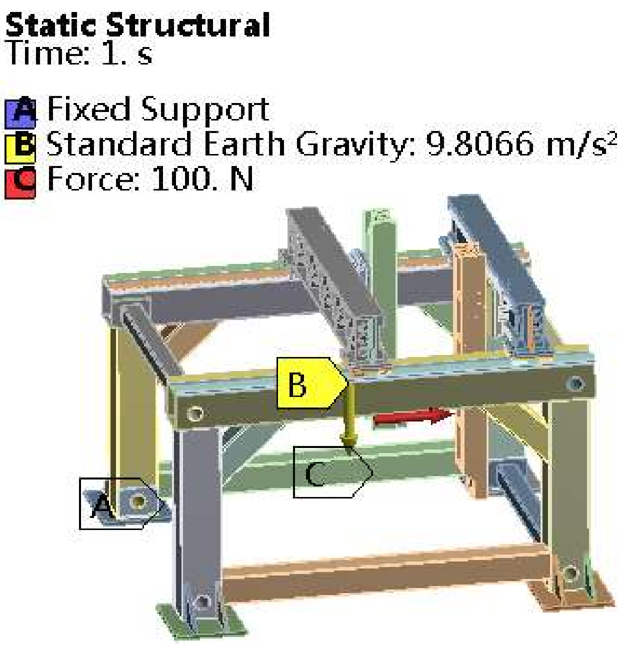

Figure 2. Boundary conditions for static analysis of vertical turning and milling structures

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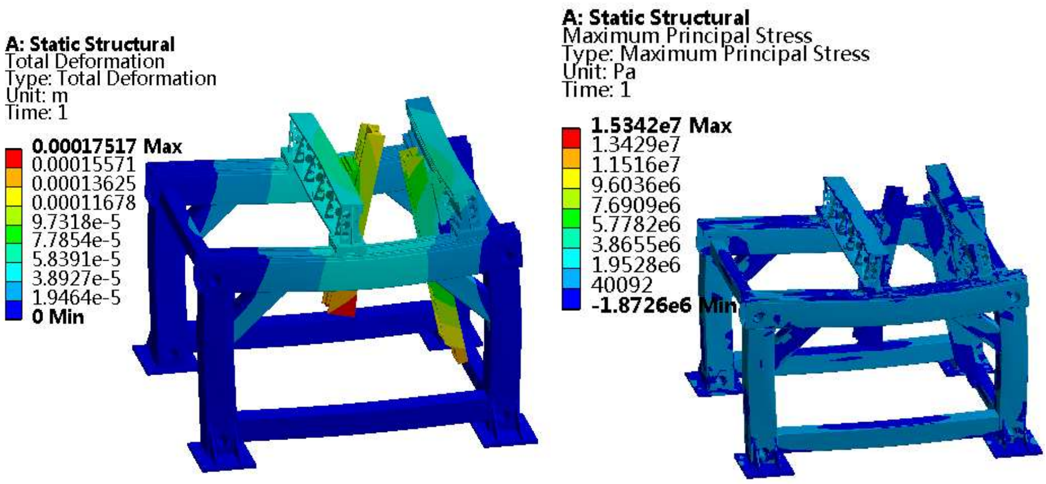
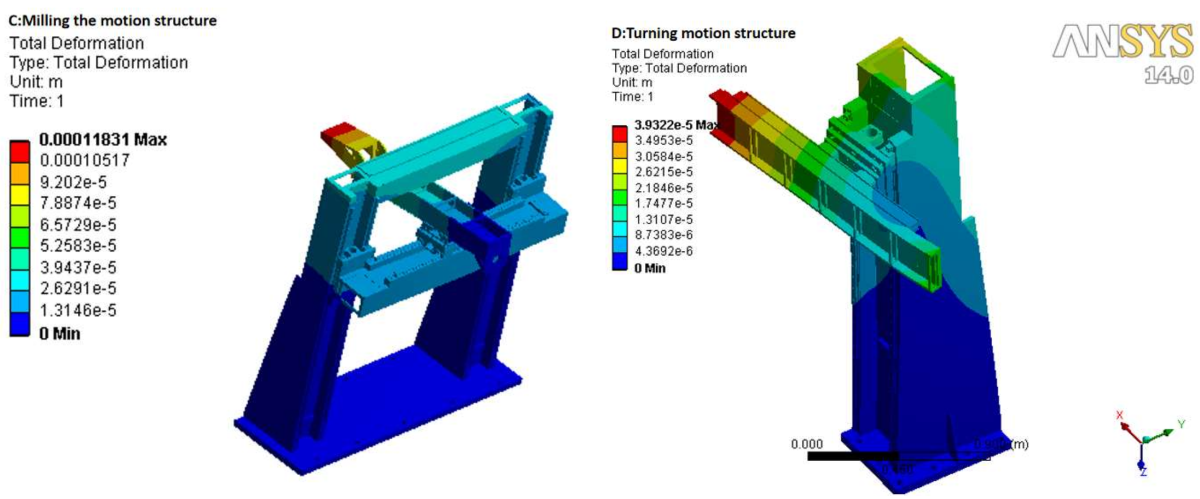


a)Maximum deformation;b)Maximum principal stress;

Figure 3. Static Analysis of Vertical Turning and Milling Structure

3.3 Analysis of Static Characteristics of Horizontal Forming Machines

The structures of the equipment turning Y-beam and the milling Y-beam are different. By establishing geometric models for the horizontal turning axle and the milling axle respectively and making corresponding structural simplifications (ignoring the transition fillet, threaded holes, and holes with a diameter less than 10mm, etc.). According to the requirements of the finite element simulation calculation, two finite element models were established. By applying the boundary conditions and loads under the same action as the vertical turning and milling structure to the finite element models respectively, the static calculation results of the horizontal digital moldless casting turning and milling compound forming machine milling shaft and the turning shaft are shown in Figures 4 (a) and 4 (b) respectively. Since the milling shaft adopts a five-axis head, the stroke and height of the milling Z-beam are both greater than those of the turning Z-beam. Therefore, only the milling shaft is analyzed during the numerical simulation calculation. The simulation results show that under the loading of the same boundary conditions, the maximum deformation of the turning structure is 0.12mm, and that of the milling structure is 0.039mm. The deformation is extremely small.



a)The maximum deformation of the milling structure;b)The maximum deformation of the vehicle structure;

Figure 4. The maximum deformation of the horizontal turning and milling structure

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4. Dynamic Characteristics Analysis of Vertical Forming Machines

4.1 Modal Analysis Theory

The establishment of dynamic models and dynamic mathematical models is the basis of modal analysis. The structure of the digital turning and milling compound moldless forming machine is relatively complex and can be simplified as a multi-degree-of-freedom linear system. Its vibration balance equation can be expressed as[19]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \tag{4}$$

In the formula: [M]It is the mass matrix;[K]It is the stiffness matrix; [C]It is the damping matrix;{F}It is the excitation force vector;$\{\ddot{x}\}$It is the acceleration vector;$\{\dot{x}\}$Is the velocity vector;{x}It is the displacement vector.

Generally, the influence of damping on modal parameters is not considered. The free vibration equation of a multi-degree-of-freedom undamped system is:

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \tag{5}$$

The displacement variable of the nodes between units can be expressed by the following formula:

$$\{x\} = \{A\}\sin(\omega t + \varphi) \tag{6}$$

In the formula:{A}It is the amplitude vector of each node, that is, the vibration mode;ω represents the corresponding natural vibration frequencies of each order;φ is the phase Angle.The formula{x}={A}(t+)Substituting into Equation (5), the expression can be obtained:

$$([K] - \omega^2[M])\{A\} = 0 \tag{7}$$

The determinant of the eigenmatrix being zero is the condition for equation (7) to have a non-zero solution, that is:

$$[K] - \omega^2[M] = 0 \tag{8}$$

Expanding this determinant yields the NTH degree equation of ω^2, in the following form:

$$\omega^{2n} + \alpha_1\omega^{2(n-1)} + \alpha_2\omega^{2(n-2)} + \cdots + \alpha_{n-1}\omega^2 + \alpha_n = 0 \tag{9}$$

The equation in Equation (9) above is called the characteristic equation. After taking the root of the characteristic values, the natural frequencies are obtained, denoted as,, and. They are called the 1st order, the 2nd order, and so on in ascending order. The NTH natural frequency.Substitute the obtained natural frequency into$[K] - \omega^2[M] = 0$， The values obtained respectively are called the first order, the second order,... The NTH order principal mode vector or amplitude vector.

4.2 Modal Analysis of Vertical Forming Machine

For structural components that are subjected to dynamic loads for a long time, it is proposed to conduct modal analysis on each motion vibration mode of the milling shaft. By analyzing and

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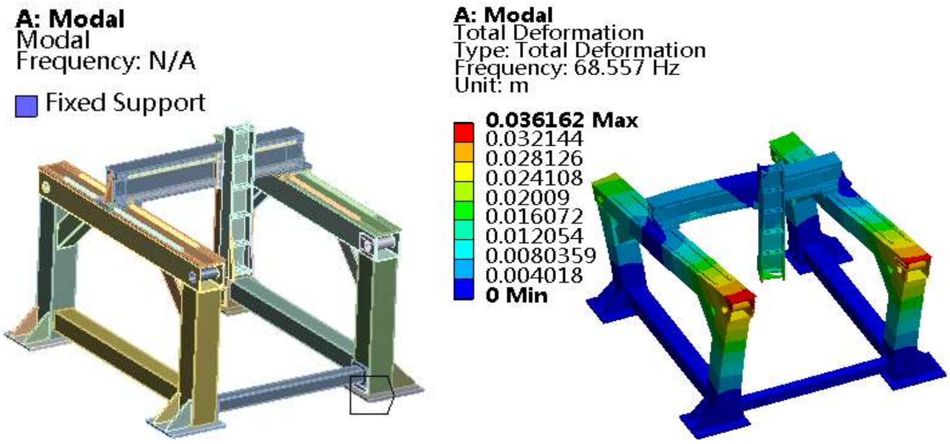
evaluating the dynamic characteristics of the structure and the form of its vibration, the damping distribution is understood, thereby avoiding the resonance that may be caused during the processing. The modal boundary conditions of the milling shaft of the vertical digital moldless casting turning and milling compound forming machine are shown in Figure 5 (a) and the modal calculation results in Figure 5 (b). The simulation results show that the 6th-order modal value of the milling shaft is 68.557.



a)Modal boundary conditions;b)Modal calculation of deformation results;

Figure 5. modal boundary conditions of milling shaft

4.3 Modal Analysis of Horizontal Forming Machine

In the modal calculation of the horizontal structure milling shaft, the modal boundary condition figure 6 of the horizontal digital moldless casting turning and milling compound forming machine milling shaft and the modal boundary condition figure 7 of the turning shaft are shown. The simulation results show that the 6th-order modal value of the milling shaft is 114.03, and the 6th-order modal value of the turning shaft is 229.22.

By deeply understanding the key links of the dynamic characteristics of the milling shaft, from the calculated deformation results, it can be seen that the milling shaft presents different deformation forms under different modes [20]. In the low-order mode, the milling shaft mainly shows overall bending deformation. This is because the vibration mode corresponding to the low-order frequency is mainly the rigid body motion of the overall structure and simple bending. This overall bending deformation may cause the milling shaft to interfere with the surrounding components during the processing, affecting the processing accuracy. It may even lead to local stress concentration and reduce the service life of the milling shaft.

With the increase of the modal order, the deformation of the turning/milling shaft gradually becomes complex, resulting in local torsional deformation and high-order bending deformation. Local torsional deformation in high-order modes will affect the rotational accuracy of the milling shaft, resulting in a change in the relative position between the tool and the workpiece, and thereby affecting the quality of the machined surface. However, high-order bending deformation may cause intensified vibration of the milling shaft, resulting in significant dynamic displacement. This not only reduces the processing efficiency but also may make the processing process unstable, increasing the risk of tool wear and damage.

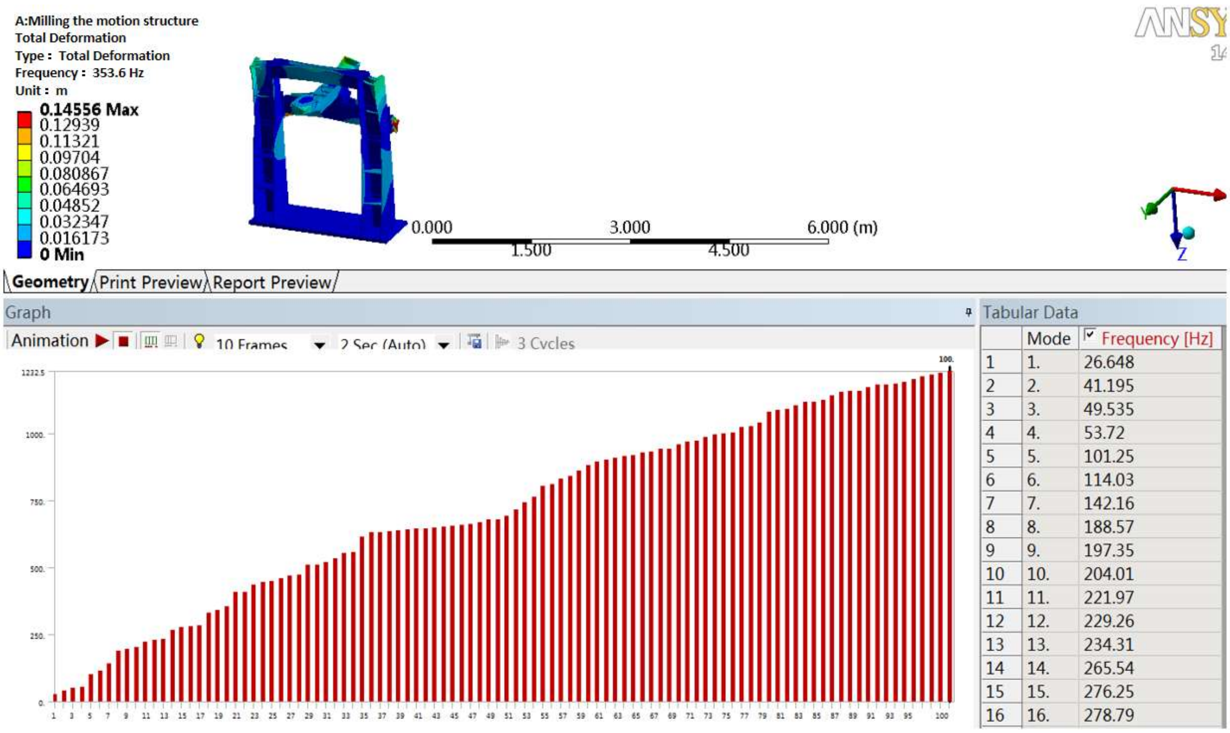


Figure 6. shows the deformation results of the modal calculation of the horizontal structure milling shaft

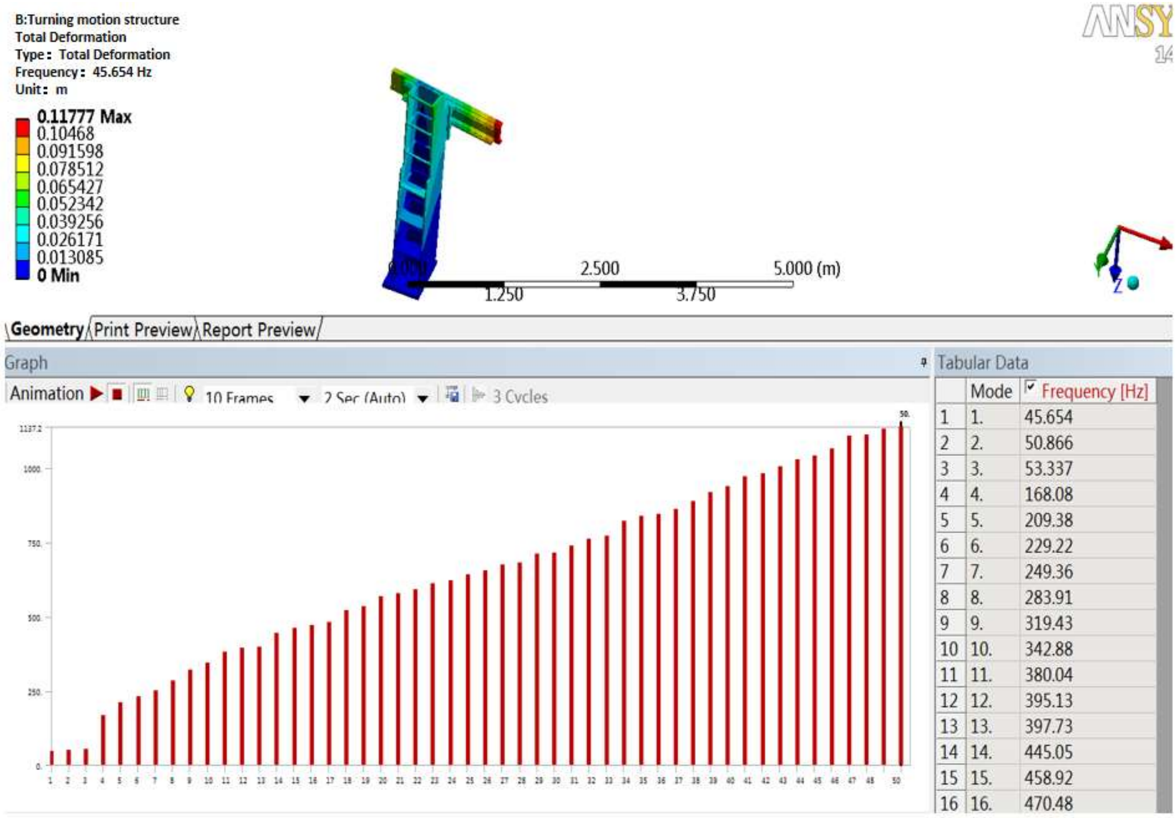


Figure 7. shows the deformation results of the horizontal structure axle mode calculation

4.4 Result Analysis of Vertical/Horizontal Turning and Milling Compound Forming Machines

The modal extraction in ANSYS was selected to analyze the vertical and horizontal turning and milling compound structures respectively, and the first six natural frequencies of the turning and milling compound forming machine could be obtained. The comparison results are listed in Table 1.

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For dynamic analysis, the modes of lower frequencies correspond to the main vibration modes of the structure. Their amplitudes are relatively large and the energy distribution is wide. Therefore, they have a greater influence in the structural response. That is, when the modal frequency of the structure is lower, the weight influence of this mode in the structural response is greater. This is because the low-frequency mode plays a significant role in the overall vibration characteristics and energy transfer of the structure, that is, the characteristics of the low-order mode basically determine the dynamic characteristics of the product.

Table 1. Comparative Analysis of the results of the first six natural frequencies

Vertical milling structure		Horizontal milling structure		Horizontal vehicle structure	
Order	Frequency(Hz)	Order	Frequency(Hz)	Order	Frequency(Hz)
1	26.372	1	26.648	1	45.654
2	34.335	2	41.159	2	50.866
3	44.407	3	49.535	3	53.337
4	56.262	4	53.72	4	168.08
5	62.603	5	101.25	5	209.18
6	68.557	6	114.03	6	229.22

As can be seen from Table 1, the fourth-order vibration mode of the horizontal turning and milling compound structure is mainly based on the deformation of the single and double beam and column structures and the Z-axis end of the turning and milling compound, which has the greatest impact on the dynamic characteristics of the entire turning and milling compound machine. Therefore, it is determined to take the vertical structure as the development target of the current turning and milling compound moldless forming machine, which can avoid blind manufacturing and improve the performance efficiency of the entire machine.

5. Application Verification of Digital Turning and Milling Compound Forming Machine

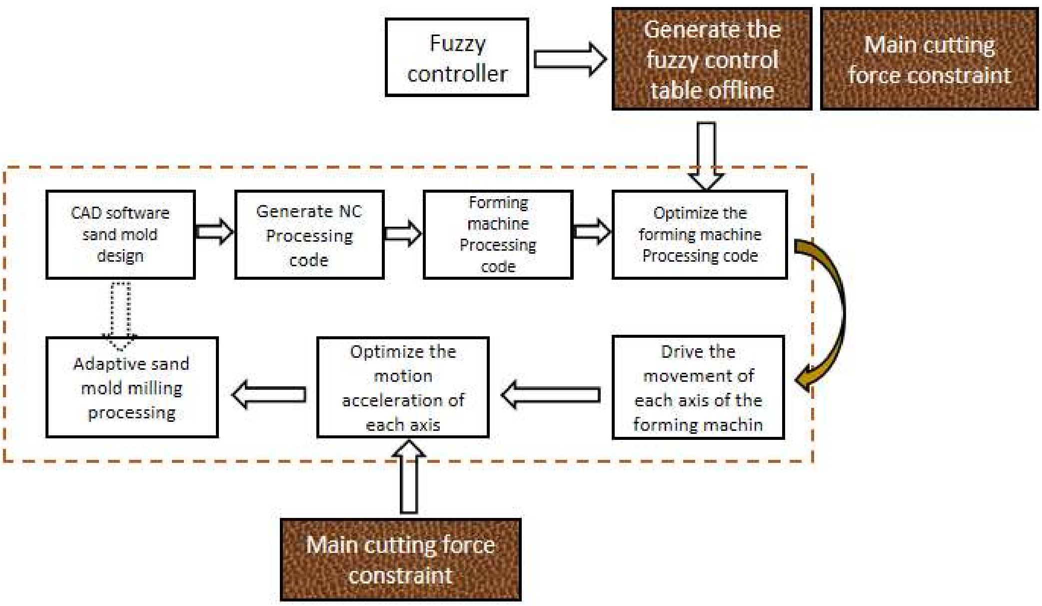

Figure 8. shows the technical flow of high-speed and high-precision sand mold cutting processing

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In view of the current industry situation where the research on the casting sand mold milling process of the digital turning and milling compound moldless forming machine is carried out less and the processing technology data is lacking, the research on high-speed and high-precision processing technology is carried out. Based on the relationship between the cutting force of the sand mold and the cutting parameters obtained through experiments, with the goal of minimizing the cutting force of the sand mold, the orthogonal experiments are adopted to obtain the optimal processing technology parameters. Under the premise of ensuring the cutting force and cutting accuracy of the sand mold, the processing code is optimized to achieve adaptive adjustment of the processing speed and maximize the processing efficiency. The process is shown in Figure 8.

Fuzzy control is designed based on the principle of high-speed and high-precision machining. The machining accuracy (∇) and cutting width (W) are taken as the inputs of the fuzzy controller, and the feed rate of the tool (v) is taken as the output of the fuzzy controller. When the input and output variables are fuzzized, the machining accuracy (∇), cutting width (W), and feed rate (v) are all defined as five fuzzy subsets {negative maximum (NB), negative medium (NM), zero (ZO), median (PM), maximum (PB)} in their domains. The membership function as shown in Figure 9 (a) is proposed to be adopted for the fuzzy subsets of the input and output variables, and the system characteristic curve is shown in Figure 9 (b).

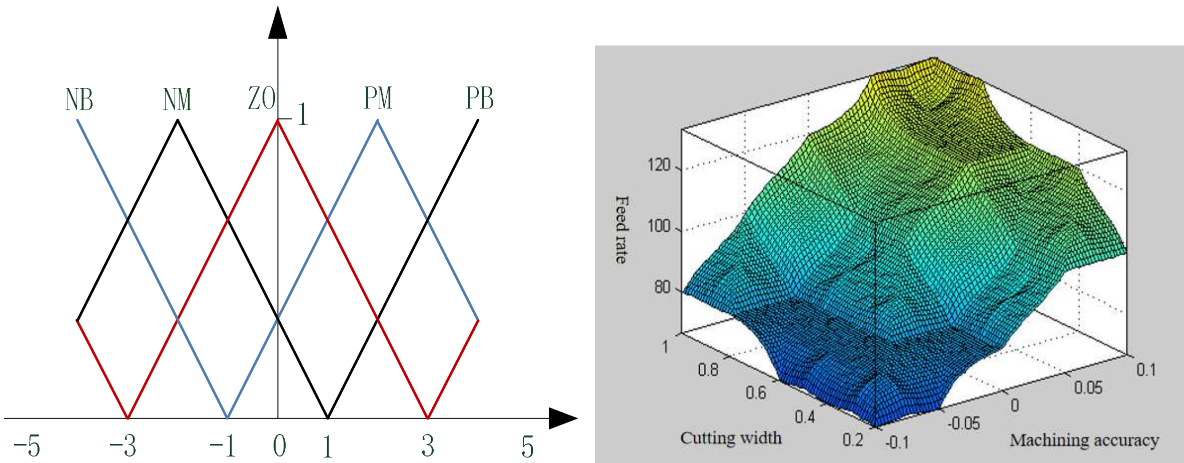

Figure 9. (a)membership functions of ∇ , W and v; (b) System output characteristic curve

For the application of the vertical digital turning and milling compound moldless forming machine, the high-efficiency and high-precision turning processing of the rotary table sand mold and the five-axis milling processing of the impeller sand mold were respectively verified.

In terms of the processing of turntable lathes, the technological characteristics are distinct. The vertical structure enables the conical table to be naturally positioned vertically under the action of gravity, and rapid and precise clamping is achieved through high-precision clamping. During processing, the chips fall in a straight line under the action of gravity, avoiding the chips from entangling the cutting tool and the workpiece, keeping the processing area clean and ensuring the continuity of the processing. The vertical arrangement of the spindle endows it with good rigidity and stability, enabling it to withstand larger cutting parameters and achieve efficient cutting. By integrating an advanced numerical control system with precise transmission components, high-precision position control can be achieved, ensuring the dimensional and shape accuracy of the truncated cone, as shown in Figure 10 (b).

(a) Cone feature model; (b) Rotary table sand mold turning processing

Figure 10. Digital turning and milling compound vertical forming machine machining

For the five-axis milling of the impeller, as shown in Figure 11 (b), the five-axis linkage function enables the tool to process the impeller from multiple angles. The tool path can be flexibly planned according to the complex curved surface shape of the impeller, effectively avoiding tool interference. The vertical structure provides a stable processing platform for the impeller, which can better adapt to the distortion of the blades and the characteristics of complex curved surfaces, and achieve high-precision curved surface processing. In addition, multiple surfaces of the impeller can be processed simultaneously, reducing processing procedures and clamping times, and enhancing processing synergy. Its advantages are significant. It can precisely control the contact Angle between the tool and the impeller surface as well as the cutting parameters, achieving high-quality surface roughness. The processing of impeller sand molds can be completed quickly through digital programming, which greatly shortens the research and development and trial production cycle of new products and reduces production costs.

(a) Impeller characteristic model;(b) Five-axis milling of impeller sand molds

Figure 11. shows the five-axis milling processing of the impeller of the digital turning and milling compound vertical moldless forming machine

With the aid of advanced simulation software, three-dimensional models of turning and milling processes are precisely constructed, as shown in Figure 12 (a). Real-time simulation analysis is conducted on tool paths, cutting parameters, material removal, etc. When milling vertical structures, in combination with a high-precision five-axis linkage system, multi-angle precise processing of

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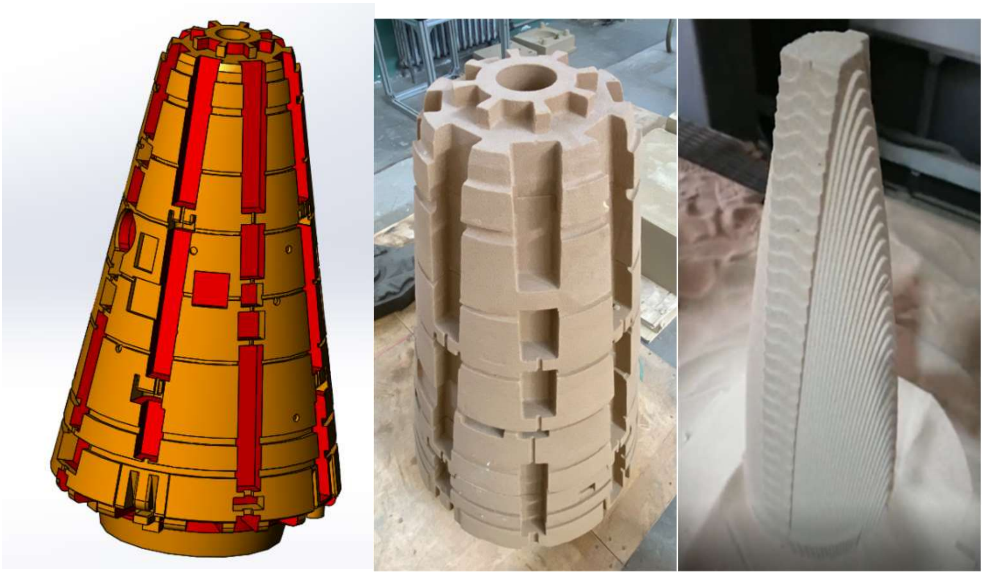
complex curved surfaces is achieved. The simulation system can, based on the shape of the workpiece and the characteristics of the material, Automatically generate the optimal tool path.

In terms of compound linkage processing, digital simulation provides reliable data support for compound processing, ensuring seamless connection between turning and milling processes. With a single clamping, multiple processing tasks can be completed, significantly improving processing accuracy and efficiency. The vertical layout endows the equipment with excellent rigidity and stability, enabling it to withstand large cutting volumes and meet the demands of efficient processing. The digital turning and milling compound moldless forming technology shortens the production cycle and reduces costs. It is particularly suitable for multi-variety and small-batch production that responds quickly to market demands. The finished products are shown in Figures 12 (b) and 12 (c).



(a) Conical core characteristic model; (b) Core sand mold of a certain type of cabin type; (c) Exhibits of turning and milling compound feature processes

Figure 12. Digital turning and milling compound vertical moldless forming machine linkage compound processing

In addition, the digital control system is easy to operate and has powerful programming functions, enabling personalized customized production. Through the organic combination of digital simulation and compound linkage processing, the digital turning and milling compound moldless forming machine provides efficient, precise and flexible processing solutions for the manufacturing industry, helping enterprises enhance their core competitiveness.

6. Conclusion and Prospect

This research explores the lightweight structural design of the digital turning and milling compound moldless forming machine. By optimizing structural parameters, selecting high-strength lightweight structural materials, and ensuring equipment performance, static analyses were conducted on vertical and horizontal turning and milling structures. The stress, strain, and displacement conditions under static loads were accurately evaluated, effectively ensuring structural stability. It has laid a solid foundation for the reliable operation of the equipment. Modal analysis clarifies the vibration characteristics and deformation laws of the structure under different modes, providing a key basis for avoiding resonance and further enhancing the dynamic performance of the equipment. After the design and analysis results of the lightweight structure were put into practical processing applications, this digital turning and milling compound moldless forming machine demonstrated significant advantages, achieving remarkable results in shortening the production cycle, improving processing accuracy and efficiency, and effectively promoting the development of the manufacturing industry towards intelligence and greenness.

In the future, with the continuous advancement of materials science, the application potential of lightweight and high-strength structures can be further explored to achieve greater lightweighting. In terms of analytical techniques, it is expected to introduce more advanced algorithms and simulation methods to enhance the accuracy and efficiency of static analysis and modal analysis. Meanwhile, efforts should be made to enhance the research and development of intelligent control systems for equipment, so that they can better adapt to lightweight structures and optimized performance, and give full play to the advantages of the equipment. It is believed that with the continuous deepening of research, digital turning and milling compound moldless forming machines will play a greater role and create higher value in the manufacturing industry.

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