Simulation and Optimization of 3 Axis Cnc Milling Machine Structure

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Abstract: - The thorough design and modeling of a 3-axis Numerical Control (NC) machine tool utilizing Solid-works, a well-known Computer-Aided Design (CAD) program, are presented in this work. The objective of this paper is to provide a more precise and comprehensive digital representation of the machine's structure, parts, and subsystems through simulation analysis that will serve as the basis for later manufacturing and operating stages.The rigidity and natural frequency of machine tools considerably influence cutting and generate great forces when the tool is in contact with the work-piece. The poor static rigidity of these Vertical machining Centre machines can cause deformations and destroy the work-piece. If the natural frequency of the machine is low or close to the commonly used cutting frequency, they vibrate considerably, resulting in poor work-piece surfaces and thus shortening the lifespan of the tool. The paper begins with an overview of the significance of 3-axis NC machines in modern manufacturing industries, highlighting their crucial role in precision machining processes among others. It emphasizes the importance of a robust and well-designed machine structure in achieving high accuracy and efficiency in producing the needed results as required. The machine's mechanical components, includes the frame, table, spindle, and tool holder, as well as its electronic systems, including the control board and motor etc, which are all carefully considered in the design process. One crucial aspect of the designing process of a NC machine is the integration of various parts into a cohesive system which ensures flawless coordination between mechanical movement and control inputs. Each machine component is modeled in 3D using Solid Works software which is generally recognized for its parametric modeling capabilities. The entire machine is simulated using the assembly capability of the program, allowing for the evaluation of clearances, inferences, and general functionality. To make sure the machine can sustain machining forces, structural integrity and stiffness are assessed using Finite Element Analysis (FEA) technique by using Abaqus 3Dsimulations software. The research concludes by showing how well Solid Works and Abaqus soft-wares works as a tool for developing and simulating 3-axis NC machines. Manufacturers may speed up their manufacturing process, identify potential problems, and optimize the design with the help of the digital representation, which is a significant resource. Additionally, it highlights how important a well-designed machine structure which is good for obtaining accuracy and dependability in contemporary machining operations.

Keywords: NC Machine,Solid works, Manufacturing, Finite element, modal analysis.

Received: May 19, 2024. Revised: January 9, 2025. Accepted: March 9, 2025. Published: June 4, 2025.

1 Introduction

Accuracy evaluation of machine tools to investigate the positioning accuracy between the tool and the work-piece is required as a criterion for acceptance testing and maintenance. In general, the accuracy is affected by various error sources, including kinematic errors, thermo-mechanical errors, loads, dynamic forces, motion control, and the control software (N. Satonakai & N. Sugimuri, et al, 2000).Process planning for materials cutting is one of the most knowledge intense activities due ti the information flow between manufacturing resources(G. Zhao, Q. Zhao et al, 2001). More efforts has since been placed into the automation of CAD/CAPP/CAM processes which are facilitated through the application of new technologies such as feature-based technologies(Ambrose R, Bekey G et al 2007) neural networks (H. Rabe, 2003),genetic algorithms (International Journal of Innovative science and Research, 2018) etc. However, there is a lack of smooth information flow between these processes since there are limited information about the manufacturing resource status.Finding solutions for this gap needs reliable and accurate realization of CNC machine specifications as well as final product requirements.

Accuracy of machined parts is one of the most critical considerations for any manufacturer. Many factors like cutting tools and machining conditions, resolution of the machine tool, the type of work-piece etc., determine the accuracy of the machined parts. As for the machine tools, there exist various error sources that make the part out of the designated accuracy. They can be classified into quasi-static errors and dynamic errors (M.A Othman, Z. Jamaludin, M. Minhat and M.A.U. Patwari, 2020) Quasi-static errors are those between the tool and the work-piece that are slowly varying with time and related to the structure of the machine tool itself. These sources include the geometric/kinematic errors, errors due to dead weight of the machine's components and thermally induced errors. Dynamic errors are caused by sources such as spindle error motion, vibrations of the machine structure, controller errors etc. Quasi-static errors account for about 70% of the total error of the machine tool and as such, are a major focus of error compensation research.

2. Objective

The objective of this study is to investigate the structure of CNC milling machine through simulation analysis and optimization. This study intends to know how the work-piece of CNC milling machine is affected during machining operations because of the structure of the CNC machine which affects the overall performances of the machine. This has been a major challenge for manufacturers.

3. CNC machine systems

The system composition of a three-axis CNC milling machine is similar to that of an ordinary milling machine tool. It is mainly composed of a spindle system, a support system, a feed system, and a control system. It controls the relative motion of the three axes of the machine tool X, Y and Z. The movement of the spindle system realizes three-dimensional CNC machining. Since the size of the components of the CNC milling machine is relatively small and the precision requirements for micro milling are relatively high, this requires that each component that makes up the machine tool has high precision to ensure the precision requirements for micro milling. At the same time, the structural optimization problems caused by the scale effect cannot be ignored in the machine tool design process (A.Khan,A.K. Shukla, and A. Singh, 2018). By controlling the relative motion of the three axes, the processing of complex parts can be realized. . However, small machine tools have problems that are different from conventional size machine tools. For example: the tools of small machine tools are very small, usually between 0.1 and 10 mm in diameter, and the spindle speed needs to be as high as tens of thousands of revolutions per minute; and the actual size of the work-piece to be processed is small, High precision requires high precision for each component of the machine tool, as well as high positioning accuracy and installation accuracy between the components as seen in Fig1 [8] .

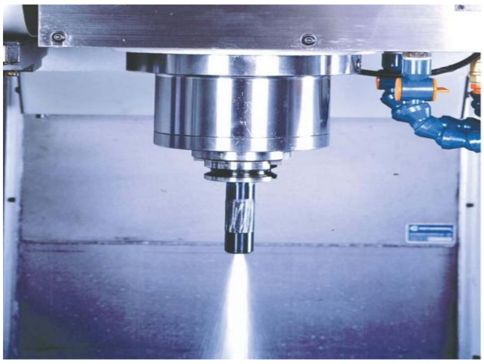

Fig 1 CNC machine tool

2.1 The Significance of 3-Axis NC Machines

Before delving into the design intricacies, it is imperative to underscore the significance of 3-Axis NC machines in contemporary manufacturing. These machines, equipped with the capability to maneuver along three orthogonal axes - X, Y, and Z, empower manufacturers to fabricate components with a degree of accuracy and precision that was once deemed unattainable. From intricate molds to aerospace components, their applications span across industries, making them indispensable tools for modern production.

2. Machine tool layout design

The machine structures are divided into open frames, closed frames, and Truss forms. The most common type of industry structure is open and closed frames, as illustrated in Fig. 1 [9]-[10]. The open frame structure is often referred to as frame C or G. This configuration is used for most conventional machine tools . On the basis of studying the development status of today's small machine tools, through market research and combining with its own actual conditions, this research group decided to develop a machine with good stiffness, high precision, easy to operate, large working range, simple structure, and the ability to realize A small three-axis linkage CNC machine tool with linear motion coordinate movement. According to the design requirements, this research proposed two overall configurations: open structure and close structure as seen in Fig 2.

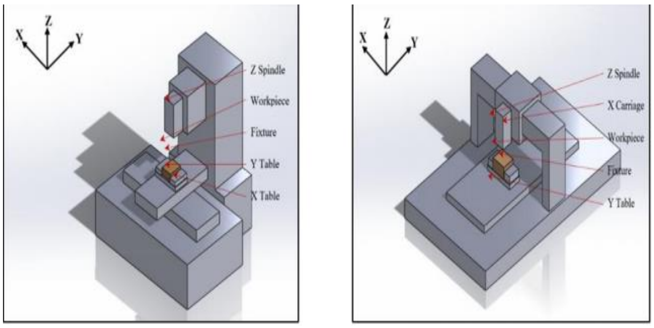

Fig 2 Open and closed frame CNC machine structure.

3.1 Power consumption

CNC machine tools have a lot of function components, and the energy consumption calculation in machining is very complex. In modern CNC machining process, the energy consumption of cutting movement is less than 15%, while the energy consumption of auxiliary systems occupies about 85%. The empirical models are advisable means to calculate energy consumption in machining . Gutowski established machine tool efficiency model and energy consumption model, and considered that machine tools consume energy even at no-load operation state . The extra energy consumption in machining is directly proportional to the material process rate, and the power balance equation is as follows:(Mativenga and Rajemi,2011).

$$P = P_0 + kv \qquad (1)$$

The variables meaning are as follows:

P is the total power in the cutting process in kW;

P0 is the idle power in kW;

k is constant in kJ/cm3;

v□ is the material processing rate in cm3/s.

Kara developed the specific energy consumption

prediction method for turning and milling process

$$SEC = C_0 + \frac{C_1}{MRR} \qquad (2)$$

where:

SEC is the machine tool specific energy

consumption in kJ/cm3 ;

C0 and C1 are constants;

MRR: the material removal rate in cm3/s.

Considering the CNC machine tool spindle drive system, no-load power consumption, standby power consumption and cutting energy consumption, Li put forward specific energy consumption prediction model in dry cutting condition.

$$SEC = k_0 + k_1 \frac{N}{MRR} + \frac{K_2}{MRR}\ ; \qquad (3)$$

The variables meaning are as follows:

k0 is the specific energy requirement in cutting

operations;

k1 is the specific coefficient of spindle motor;

k2 is the constant coefficient of machine tool;

N is the spindle speed;

MRR is the material removal rate in cm3/s.

In CNC turning and milling, the cutting elements commonly include the spindle speed, feed rate and cutting depth. Specifically, the spindle speed is used to specify the CNC machine tool spindle rotation rate in r/min; feed rate is the moving speed of the tool relative to work piece on the feed direction in mm/min; and cutting depth is the vertical distance between the machined surface and the unprocessed surface in mm. Machining process is a dynamic system, which cuts work piece material with cutter, fixture, lubricating oil and coolant, and finally obtains the semi-finished or finished products. All of the process stages need to consume energy. Each subsystem of mechanical processing is accompanied with the energy input, storage and release, loss and output. In general, the energy required for machining system is electric energy.

4 Structure Simulation and Analysis

4.1 Simulation analysis

Abaqus in FEA (Finite element analysis) is divided into 3 categories: 1. Abaqus standard be used for general analytical, 2. Abaqus Explicit be used for a analytical dynamic structure, 3. Abaqus CAE be used for complex analytical for modeling, analysis, monitoring and visualizing simulation. In this research, Abaqus CAE is used for analysis. Stress analysis, safety factor and displacement had been studied in this research. The step of the simulation on Abaqus can be seen on the Fig. 3

During the structural simulations analysis of machine frame using abaqus simulations software, aluminum material with the density of 2700kg/m^3, Young's modulus 69000 MPa and a Poisson's ration 0.33 MPa was selected to be used for the analysis. The frame structure and machine parts are custom-made from the aluminum extrusion profile. Aluminum extrusion is suitable for building frame structures because it is easy to mount and assemble and corrosion-resistant or flexible. Because of its lightweight design, aluminium was also chosen for sufficient strength to hold parts without deformation.

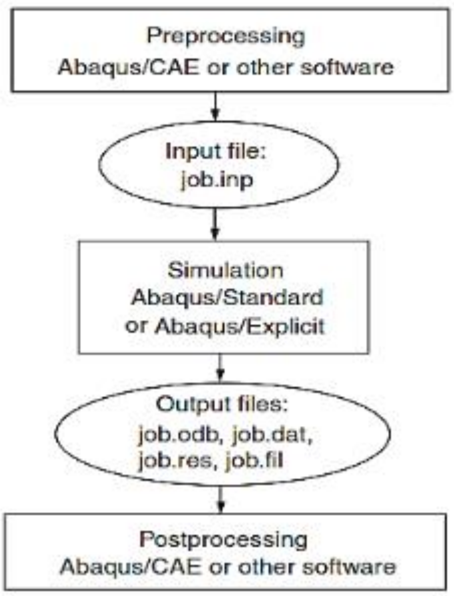

Fig 3: Step for FEM analysis on Abaqus

4.2 Static Analysis

This section mainly studied the static response of the machine tool under the action of gravity and cutting force of each component. By analyzing the static displacement and stress of the machine components, its static stiffness and strength can be obtained. After assigning material properties to each component of the machine structure, the quality of the main structure of the machine can be obtained, as shown in Table 1.

During the static analysis process, the element type was C3D10 and 14546 elements were generated during the analysis with the first two analysis results being recorded and used for our analysis the results can be seen in Fig 4 &5 below. Since the static stiffness of the beam structure of the model in the original structure which needs to be improved, and the optimized X-axis support component replaces the beam in the original structure to support the main axis component and Z-axis component, it was necessary to conduct a static analysis of the X-axis support component. We loaded the three-dimensional model of the X-axis support component into Workbench, apply the gravity load borne by the X-axis support component at the corresponding part, and then we obtained the total deformation cloud diagram of the Y-direction deformation cloud as shown in Figure 4, the Z-direction deformation cloud is shown in Figure 5 and the equivalent stress cloud is shown in Figure 6.

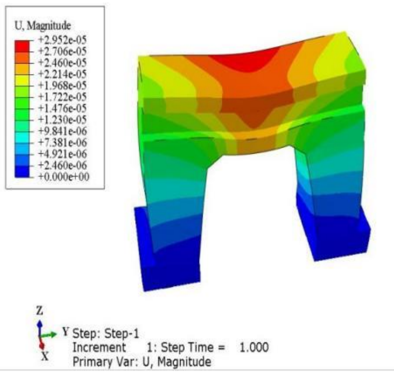

Fig 4 Stress analysis (Magnitude)

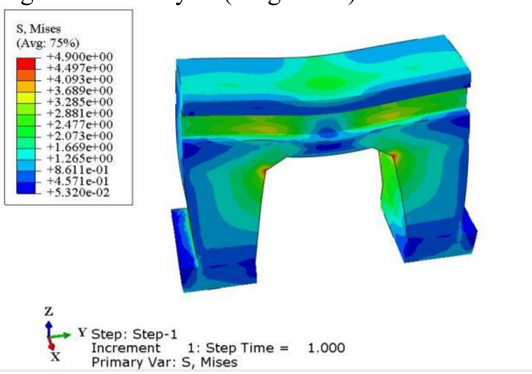

Fig 5. Stress analysis(Mises)

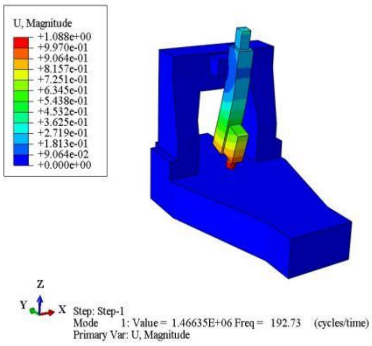

Fig 6. Assembly analysis

Table 1 Structural quality of machine tools

structure	Spindle parts	Column	beam	workbench	X Shaft parts	Y Shaft parts	Z Shaft parts
quality	9.64kg	27.47kg	23.56kg	6.84kg	29.58kg	19.36kg	16.25kg

From the above static analysis results, it can be seen that the maximum deformation of the machine tool is the Z-axis motor, with the maximum value of about 12 μm. The main reason for the maximum deformation is the superposition of the Z-direction displacement of the machine tool components below the Z-axis motor caused by gravity; the deformation of the beam the largest part is the connection with the Z-axis component, and the maximum deformation is about 5.4 μm. This part bears the gravity of the main axis component and the Z-axis component, and the self-weight of the beam is also applied here; the deformation of the upper part of the column is about 3.5μm, the deformation amount decreases from top to bottom. The maximum displacement of the beam is too large, which is greater than the accuracy required by the machine tool design, that is, the static stiffness of the beam is low, and the beam structure needs to be optimized to improve its static stiffness.

It can be seen from Figure 5 that the main parts that generate stress are the beam, column and the electric spindle near the tool end. The stress value at these parts is about 1.43MPa. The maximum stress occurs at the connection between the beam and the Z-axis component. The maximum stress value is about the yield strength of 4.68MPa is much smaller than that of HT250, which is 250MPa, indicating that the milling machine meets the strength requirements.

4.3 Modal analysis

Modal and Harmonious response analysis is the main method of Dynamic research. Modal analysis is a numerical technique for calculating the vibration characteristics of structures. It main purpose is to obtain the natural frequencies and modes of structures. Modal analysis can effectively avoid resonance or vibration at a specific frequency.

The dynamic equation for undamped modal analysis is: $[M]\{X''\}+[K]\{X\}=\{0\}$ (1)

The free vibration of the structure is simple harmonic vibration, so the displacement is:

$X = x\sin(\omega t)$ (2)

The equation (3) is obtained by introducing (2) into (1).

$$([K]-\omega^2[M])\{X\}=\{0\} \quad (3)$$

From equation (3), eigenvalues and corresponding eigenvectors can be calculated, in which eigenvalues ω_i are natural circular frequencies and eigenvectors $\{x\}i$ are vibration modes.

Modal analysis contain three types of analysis which include: Free modal analysis, Constrained modal analysis, Pre-Stress modal analysis. For our analysis, we used the Free modal analysis with the number of elements being the same as the static analysis.

Generally, low-order modes have a greater impact on the dynamic characteristics of the structure. Therefore, only the first six-order calculation results are extracted for the modal analysis of the machine tool along with the first 20 model elements, so that the dynamic characteristics of the structure can be obtained accurately and quickly. Through modal analysis of the whole machine, the mode shape diagram of each order is obtained, as shown in fig 7-19.

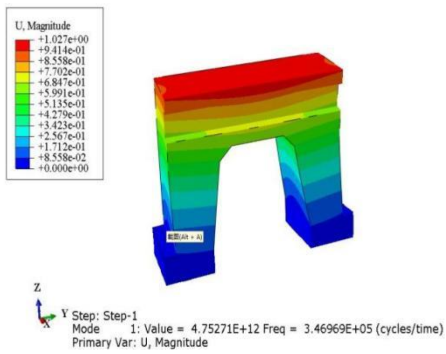

Fig 7 First-order mode shape diagram

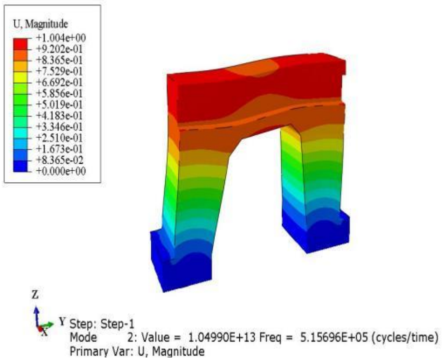

Fig 8 second-order mode shape diagram

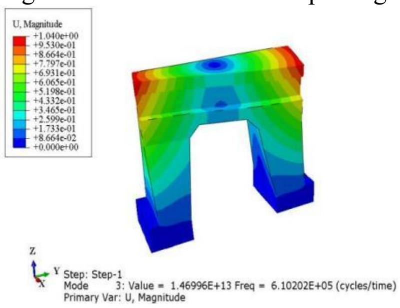

Fig 9 3rd-order mode shape diagram

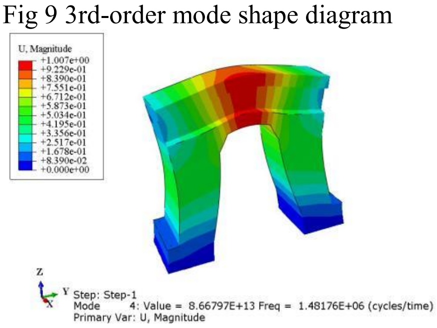

Fig 10 4th order mode shape diagram

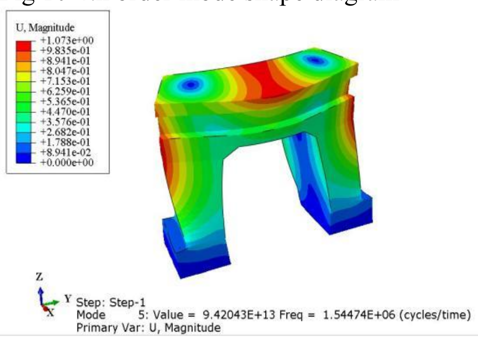

Fig 11 5th order mode shape diagram

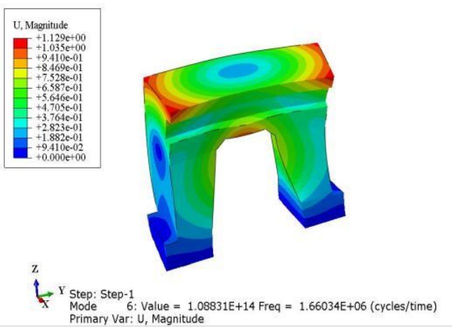

Fig 12 6th-order mode shape diagram

Index	Description			
0	Increment	0: Base State		
1	Mode	1: Value = 1.46635E+06	Freq = 192.73	(cycles/time)
2	Mode	2: Value = 1.71239E+06	Freq = 208.27	(cycles/time)
3	Mode	3: Value = 2.73063E+06	Freq = 263.00	(cycles/time)
4	Mode	4: Value = 5.33023E+06	Freq = 367.45	(cycles/time)
5	Mode	5: Value = 1.08761E+07	Freq = 524.87	(cycles/time)
6	Mode	6: Value = 1.69669E+07	Freq = 655.57	(cycles/time)
7	Mode	7: Value = 2.83508E+07	Freq = 847.43	(cycles/time)
8	Mode	8: Value = 5.40687E+07	Freq = 1170.3	(cycles/time)
9	Mode	9: Value = 6.86860E+07	Freq = 1319.0	(cycles/time)
10	Mode	10: Value = 7.34013E+07	Freq = 1363.6	(cycles/time)
11	Mode	11: Value = 8.33654E+07	Freq = 1453.2	(cycles/time)
12	Mode	12: Value = 9.08836E+07	Freq = 1517.3	(cycles/time)
13	Mode	13: Value = 1.05082E+08	Freq = 1631.5	(cycles/time)
14	Mode	14: Value = 1.14784E+08	Freq = 1705.1	(cycles/time)
15	Mode	15: Value = 1.26813E+08	Freq = 1792.3	(cycles/time)
16	Mode	16: Value = 1.37149E+08	Freq = 1863.9	(cycles/time)
17	Mode	17: Value = 1.47551E+08	Freq = 1933.3	(cycles/time)
18	Mode	18: Value = 1.78836E+08	Freq = 2128.4	(cycles/time)
19	Mode	19: Value = 2.31972E+08	Freq = 2424.0	(cycles/time)
20	Mode	20: Value = 2.59592E+08	Freq = 2564.3	(cycles/time)

Fig 13 Model analysis (Assembly 20 Mode elements)

The natural frequencies and main vibration shape results of the first six modes of the whole machine are shown in Table 2

Table 2 The first six natural frequencies and main vibration modes of the complete machine.

Order	Natural frequency(Hz)	Main vibration mode
1	192.73	The gantry swings back and forth, and the Z-axis motor vibrates.
2	208.27	Z-axis support frame swings forward and backward
3	263.00	The gantry swings left and right, and the Z-axis bracket and spindle vibrate.
4	367.45	Y-axis motor vibrates up and down
6	524.87	The gantry is slightly deformed, and the Z-axis motor and spindle vibrate.

6	655.57	The shoulders on both sides of the gantry swing symmetrically forward and backward

It can be seen from the modal analysis results that the first six-order natural frequency range of the CNC milling machine structure is 192.73~655.57Hz. The Z-axis support frame and its supported spindle components are prone to vibration, and the CNC machine frame is prone to dynamic deformation and displacement. Therefore, the gantry structure Needs optimization.

5 Structure Optimization and analysis

5.1 Analysis of static and dynamic characteristics of machine tools during optimization

After modeling CNC machine model using Solid-works, many small structures in the model increased the difficulty of meshing by Abaqus 3D simulation software. The increase in the number of meshes will prolong the calculation time and affect work efficiency. Therefore, before conducting finite element analysis on a CNC machine, the three-dimensional model of the machine tool needs to be simplified to a certain extent. Characteristics such as chamfer, holes, and grooves that have little impact on the deformation and internal force distribution of the machine tool structure need to be ignored. Appropriate simplification will not affect the structure of the machine tool. Complex cross-sectional characteristics of the overall structure of the machine tool. The integration of optimal design technology and finite element analysis methods has been instrumental in the development of computers, particularly in the field of structural optimization design. Designers now have the ability to employ finite element analysis software, which enables them to conduct swift and dependable analyses, leading to optimized structures. Consequently, this enhancement in efficiency not only reduces workload but also improves the overall quality of design, ultimately resulting in reduced development costs.

When optimizing the design of large-scale mechanical components with complex structures, due to their complex structures and large volumes, the process of establishing a three-dimensional model will be cumbersome. The number of finite element meshes is also too large, and the computer hardware for finite element analysis is very demanding. The computing speed and running memory requirements are also very high. These will cause problems such as long optimization time and consumption of a large amount of resources, and may even lead to optimization failure. Therefore, in order to avoid the above problems, this article uses the selection optimization method to optimize the design of important components of the three-axis linkage CNC milling machine

5.2 Optimization

This section will conduct a static and modal analysis of the optimized machine and compare it with the analysis results of the original plan. The advancement of computers technology has integrated optimal design technology and finite element analysis methods and applied them to structural optimization design. With the use of finite element analysis software,designers can efficiently and reliably analyze and optimize structures, effectively improving efficiency while reducing workload. Improve design efficiency and quality, reducing development costs. When optimizing the design of large-scale mechanical components with complex structures, due to their complex structures and large volumes, the process of establishing a three-dimensional model will be very troublesome, and the number of finite element meshes is also too large, which requires a lot of computer hardware for finite element analysis. The computing speed and running memory requirements are also very high. These will cause problems such as long optimization time and consumption of a large amount of resources, and may even lead to optimization failure. Therefore, in order to avoid the above problems, this article uses the selection optimization method to optimize the design of important components of the small three-axis linkage CNC milling machine.

5.3 Static analysis after optimization

After solid modeling of a CNC milling machine using Solid-works, many small structures in the model will increase the difficulty of meshing by Abaqus. The increase in the number of meshes will prolong the calculation time and affect work efficiency. Therefore, before conducting finite element analysis on a CNC milling machine, it is necessary to simplify the three-dimensional model of the machine tool to a certain extent, ignoring features such as chamfer, holes, and grooves that have a small impact on the deformation and internal force distribution of the machine tool structure. Appropriate simplification will not affect the Complex cross-sectional characteristics of the overall structure of the machine tool. The simplified three-dimensional model of the machine tool as well as the total deformation cloud diagram of the machine tool are shown in Figure 14-17.

From the static analysis of the original machine tool, it can be seen that the static stiffness of the machine tool's as well as its modal structure is low, and the static displacement of the machine tool needs to be reduced under the condition of bearing the self-weight of each component. It can also be seen from the static analysis results of the optimized machine structure that the static stiffness of the structure after structural optimization meets the design requirements. Except for the change in gravity, other parameters are the same as those set for the static analysis of the entire machine in the original plan to ensure that the analysis results are accurate and comparable.

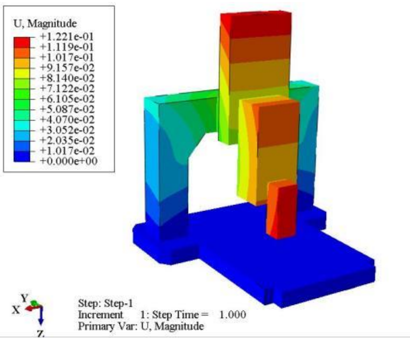

Fig 14 Total deformation of the model

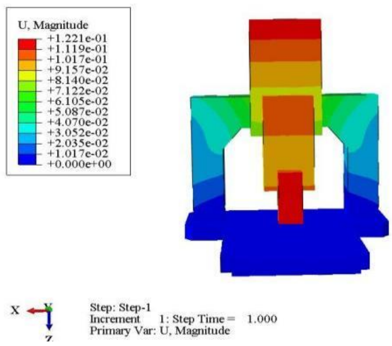

Fig 15 X direction deformation of the model

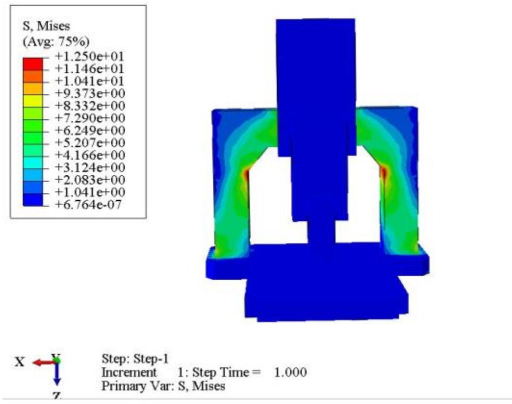

Fig 16 Y direction of the model

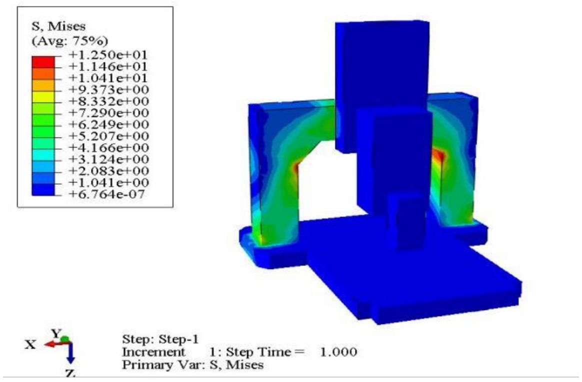

Fig 17 Z direction of the model

Optimization in the context of 3-Axis CNC machines transcends mere speed enhancement. It encompasses a holistic approach that amalgamates mechanical design, control systems, tooling strategies, and material considerations.

Comparison between the static analysis results of the entire machine in the original plan with that of the static analysis results of the optimized machine is shown below in table 3

Table 3 Comparison of static analysis results before and after machine tool optimization

	Maximum deformation	Maximum deformation in X direction	Maximum deformation in Y direction	Maximum deformation in Z direction	Maximum stress

Before optimization	10.65μm	2.50μm	9.31μm	6.81μm	6.68MPa
After optimization	7.45μm	1.35μm	6.24μm	3.84μm	0.61MPa

Table 3 as shown above shows that, following optimization, the maximum deformation of the complete machine tool is decreased by 3.2 μm. The primary cause is that, following optimization, the gantry beam's static stiffness in the original plan increased, and the static displacement in the X, Y, and Z directions all decreased. The maximum deformation amount in the X direction is reduced by 1.15μm, the maximum deformation in the Y direction is reduced by 3.07μm, the maximum deformation in the Z direction is reduced by 2.97μm, the maximum stress reduction is 6.07MPa. The maximum deformation in the optimized machine tool's static stiffness and strength also improved, demonstrating that the optimized machine tool structure's static characteristics are superior to those of the original machine tool structure.

5.4 Modal analysis after optimization

We import the three-dimensional model of the optimized machine tool into the Abaqus simulation software, set the same material parameters as the machine tool before optimization, then we divide the mesh and solve it, and obtain the first six-order modal analysis of the optimized machine tool, as shown in Figure 18-24.

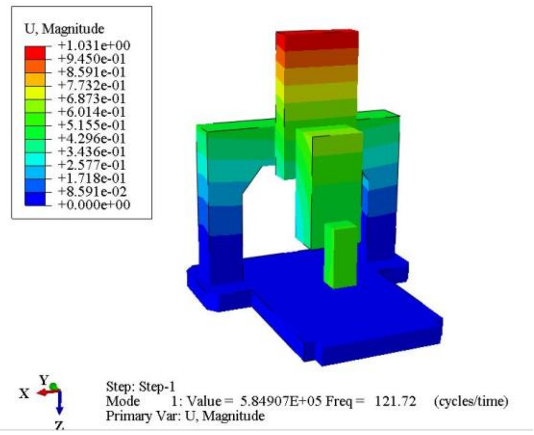

Fig 18 First-order mode shape diagram

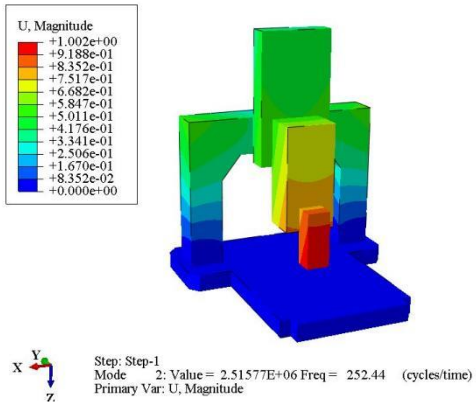

Fig 19 second-order mode shape diagram

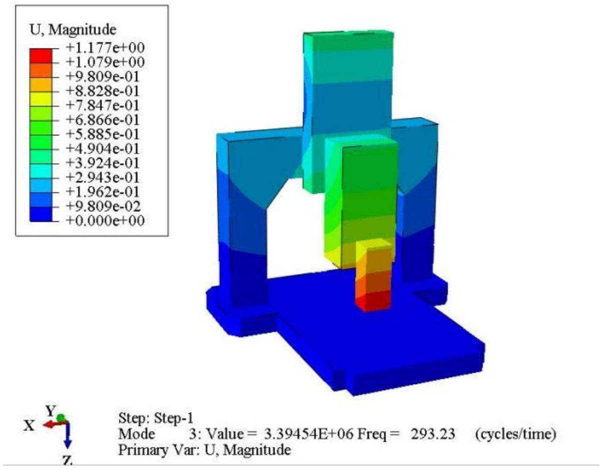

Fig 20 third-order mode shape diagram

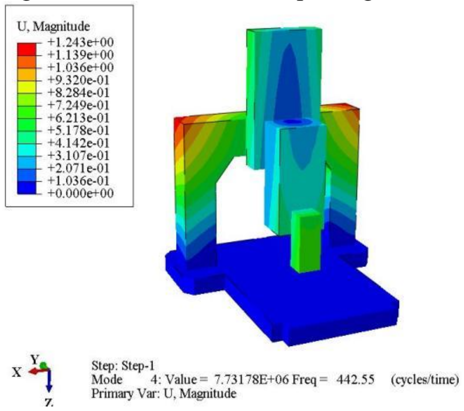

Fig 21 Fourth-order mode shape diagram

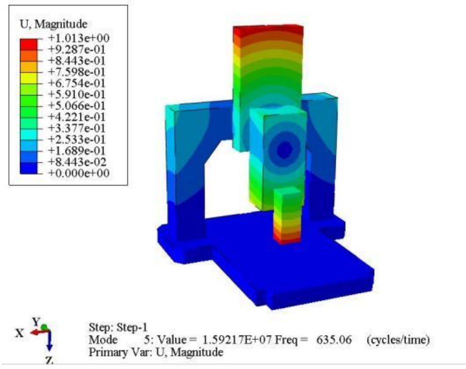

Fig 22 Fifth-order mode shape diagram

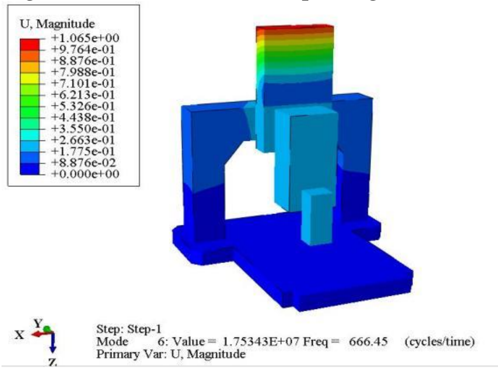

Fig 23 sixth-order mode shape diagram

Index	Description			
0	Increment	0: Base State		
1	Mode	1: Value = 5.84907E+05 Freq =	121.72	(cycles/time)
2	Mode	2: Value = 2.51577E+06 Freq =	252.44	(cycles/time)
3	Mode	3: Value = 3.39454E+06 Freq =	293.23	(cycles/time)
4	Mode	4: Value = 7.73178E+06 Freq =	442.55	(cycles/time)
5	Mode	5: Value = 1.59217E+07 Freq =	635.06	(cycles/time)
6	Mode	6: Value = 1.75343E+07 Freq =	666.45	(cycles/time)
7	Mode	7: Value = 3.16957E+07 Freq =	896.02	(cycles/time)
8	Mode	8: Value = 6.63384E+07 Freq =	1296.3	(cycles/time)
9	Mode	9: Value = 6.94176E+07 Freq =	1326.0	(cycles/time)
10	Mode	10: Value = 8.97226E+07 Freq =	1507.5	(cycles/time)
11	Mode	11: Value = 1.20374E+08 Freq =	1746.2	(cycles/time)
12	Mode	12: Value = 1.41181E+08 Freq =	1891.1	(cycles/time)
13	Mode	13: Value = 1.99621E+08 Freq =	2248.7	(cycles/time)
14	Mode	14: Value = 2.00141E+08 Freq =	2251.6	(cycles/time)
15	Mode	15: Value = 2.08676E+08 Freq =	2299.1	(cycles/time)
16	Mode	16: Value = 2.09594E+08 Freq =	2304.1	(cycles/time)
17	Mode	17: Value = 2.32258E+08 Freq =	2425.5	(cycles/time)
18	Mode	18: Value = 2.88192E+08 Freq =	2701.8	(cycles/time)
19	Mode	19: Value = 2.99321E+08 Freq =	2753.5	(cycles/time)
20	Mode	20: Value = 4.20364E+08 Freq =	3263.1	(cycles/time)

Fig 24 20 modes values

6. Harmonic response analysis

Harmonic response analysis is to analyze the response of the structure under harmonic loads of different frequencies and amplitudes. By detecting the resonance, the weak stiffness of the structure can be found, so as to achieve the targeted structural optimization and improvement. The natural frequencies and modes of the structure are obtained by modal analysis, and the influence of external forces at different frequencies on the structure can be obtained by harmonic response analysis. When the load of the structure changes with time according to the harmonic law, its equation is as follows:

$$[M]\{x''\}+[C]\{x'\}+[K]\{x\}=\{F\} \quad (1)$$

Since {F} and {x} represent harmonic load and displacement respectively, the following relations can be obtained:

$$\{F\}=\{F_{max}e^{j\Psi}\}e^{j\omega} = (\{F_1\}+i\{F_2\})e^{j\omega} \quad (2)$$

$$\{X\}=\{X_{max}e^{j\Psi}\}e^{j\omega} =(\{X_1\} + i\{X_2\})e^{j\omega} \quad (3)$$

Where, ω is the frequency of Excitation load; Ψ phase angle of exciting load; $\{F_1\}$ is the real part of the load; $\{F_2\}$ is imaginary part of the load; $\{X_1\}$ is real parts of displacement; $\{X_2\}$ is imaginary parts of displacement.

Equations (2) and (3) are introduced into equation (1) to obtain the characteristic equation of harmonic response analysis.

$$([K]-\omega^2[M]+i\omega[C])(\{X_1\}+i\{X_2\})=(\{F_1\}+\{F_2\}) \quad (4)$$

As can be seen from Figure 25, after the CNC milling machine cutter point is subjected to the excitation force in three directions XYZ, there is a significant large displacement along the X direction near the mode frequencies of order 2,3,5 and 7. As can be seen from the below mode figure, the fifth mode mode is the table twisted vibration around the Y direction.

Also as can be seen from Figure 27 below, after the CNC milling machine cutter point is subjected to the excitation of force in three directions XYZ, there is a significant large displacement along the Y direction near the mode frequencies of order 3,5 and 6. As can be seen from the mode mode below, the sixth mode mode is at the center of the connecting plate between the the column and the Y axis vibrates in the positive direction of the Z axis.

Lastly, as can be seen from Figure 28,after the milling machine cutter point is subjected to the excitation force in three directions XYZ, there is a significant large displacement along the Z direction near the mode frequencies of order 2,4, and 6. As can be seen from the mode mode figure below, the sixth mode mode is Y axis and Z axis frame torsion and vibration around Z axis. Because of the structure and constraints of the machine tool column, the response of each point on it is different. Considering that the are matched with the spindle box directly affects the processing accuracy, the displacement response value of this area is focused on as shown below in Figure 28 below.

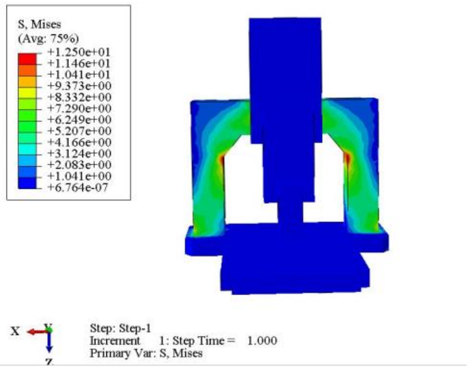

Fig 25 Areas of focus

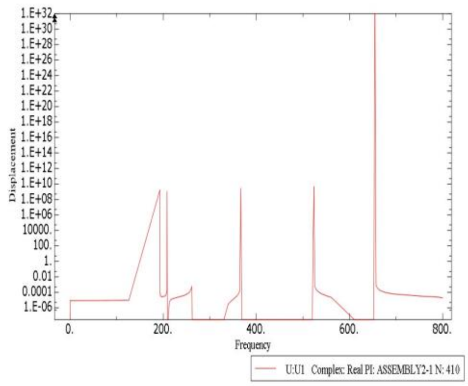

Fig 26 X-direction displacement response

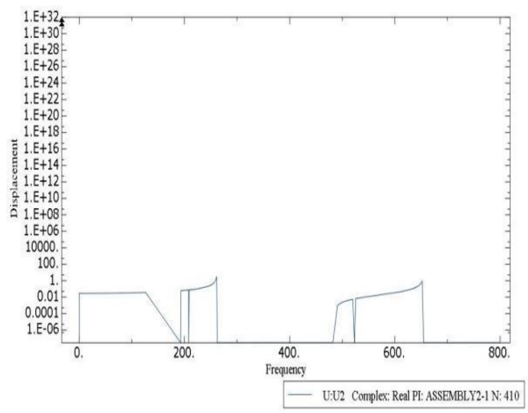

Fig 27 Y-direction displacement response

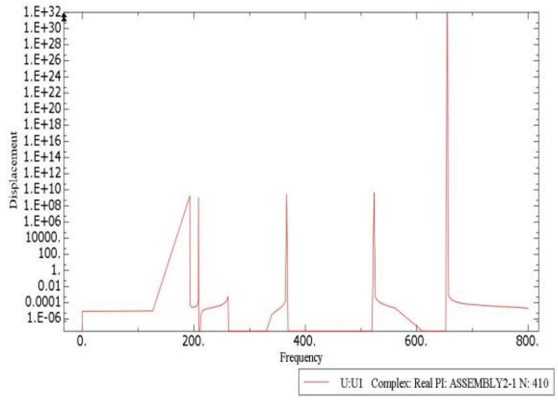

Fig 28 Z-direction displacement response

7. Conclusions

Based on the digital simulation technology and experimental design, the dynamic characteristics of the column and structure of a NC machine tool are studied. First, the natural frequencies and modes of the structure are obtained by modal analysis through the used of finite element analysis software (ABAQUS), and then the responses of the structure to external forces at different frequencies are obtained by harmonic response analysis. Finally, the lightweight design of the machine structure is realized, and good dynamic characteristics are guaranteed.

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