Dynamic Characteristics Analysis of a Micro Grinding Machine Tool

Wei Li , BeizhiLi and Jianguo Yang

College of Mechanical Engineering, Donghua University, Shanghai, 201620, China

Abstract. Developing miniaturizedultraprecision machine tools (MUMTs) is a rational approach to manufacture micro/mesoscale mechanical components. The dynamic characteristics of MUMTs can be different from that of conventional machine tools, because of its miniaturized structure, downsized components and more flexible assembly. Their dynamics behaviorneeds to be studied. In this paper, the dynamic characteristics of a verticalultraprecisionmicro grinding machine tool were analyzed. An analysis model was established based on finite element method(FEM).Modal analysis was then conducted to obtain vibration mode characteristics of the machine tool, and then the harmonic response analysis was applied to machine tool for verifying its mechanical behaviour. This work helps MUMT developers make a better product at the early design stage with lower cost and development time

1 Introduction

Currently, most of the micro/mesoscale mechanical components are machined by conventional ultra-precision machine tools and MEMS manufacturing techniques. A rational approach for micro/mesoscale manufacturing is to develop miniaturized ultra-precision machine tools(MUMTs). The advantages of MUMTs include: small footprint, low cost of energy, low operational costs, quick response to demands,etc.[1].

Dynamic characteristics of machine tools structure have an important influence on cutting efficiency and machining accuracy. They are important performance indicator of machine tool and have been widely studied for design and optimization of conventional machine tools to enhance their machining performance[2-5]. Dynamic characteristics of miniaturized ultra-precision machine tools also need to be analyzed for structure optimization and performance enhancement. In this paper, the dynamic characteristics of a verticalultra-precisionmicro grinding machine tool were researched based on finite element method(FEM).The natural frequency, vibration modes and displacements of dynamic response were analyzed.

2 Theory of dynamic analysis

Dynamiccharacteristics analysis of the machine tools incl udes modal analysis and harmonic response analysis.

2.1 Theory of modal analysis

Modal analysis is used to determine the vibration characteristics of the structure, it is also the basis for the analysis of the harmonic response [6]. The Eigen frequency equation for modal analysis is given by:

$$\left(K - M\omega_i^2\right)\varphi_i = 0 \tag{1}$$

where K is symmetric stiffness matrix of the structure, $M$is symmetric mass matrix, ω is the natural frequency, and φ is the vibration mode.$i$is the number of modes, and it is equal to the number of degrees of freedom.

2.2 Theory of harmonic response analysis

Harmonic response analysis predicts the response of a structure subjected to continuous harmonic excitation. There are many forced vibration in engineering applications, the vibration is caused by disturbance force or displacement. The dynamic equations of motion can be expressed as:

$$M\ddot{x} + I - P = 0 \tag{2}$$

where M is symmetric mass matrix of the structure, I is internal forces, P is external forces, $\ddot{x}$ is acceleration. By solving equation (2),the steady state response of the structure generated by excitation can be obtained.

3 FEM model

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. FEM cuts a structure into several elements (pieces of the

DOI: 10.1051/matecconf/20179507002

structure), then reconnects elements at "nodes", as if nodes were pins or drops of glue that hold elements together. This process results in a set of simultaneous algebraic equations. The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variational methods from the calculus of variations to approximate a solution by minimizing an associated error function. Abaqus is one of the outstanding commercial FEM softwares applied to a wide variety of engineering problems. Its accuracy of calculation results have been verified by many experiments.

The main components of the vertical micro grinding machine tool are machine bed, column, spindle, stages. All the stages are set in their initial position. The 3D model of the machine tool was established in Solidworks, and then imported into Abaqus to get the finite element model. In the FEM simulations, tetrahedron elements defined by 10 nodes are suitable for irregular geometry. Meshing were used to mesh the virtual machine structure. The bottom surface of the 3D structure was constrained during the whole computations. Most of the components are connected by bolts, such as the connection between machine bed and column, spindle and stage in z direction. These connection are simulated by bolt load model in Abaqus. The relationship between carriage and base of the stage was simulated with linear spring elements and an example is shown in Fig. 1.

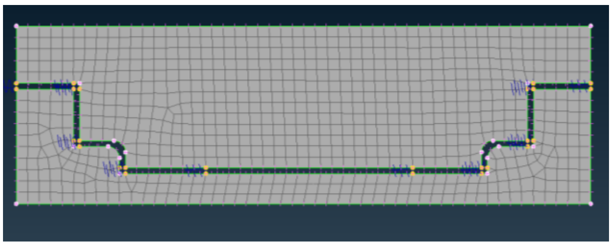
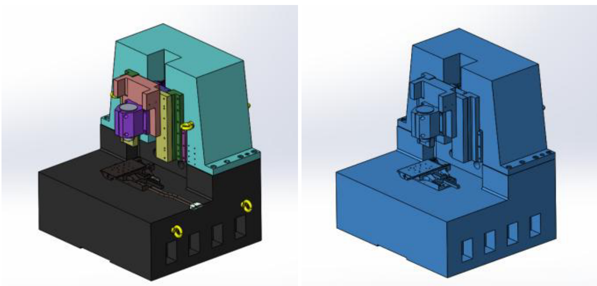


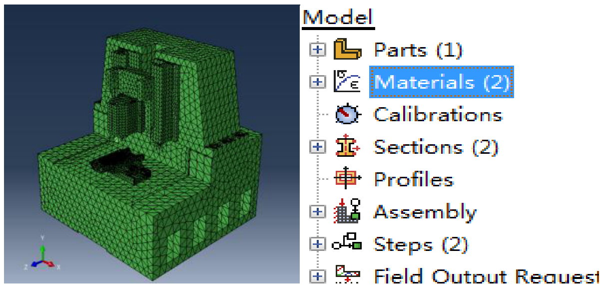
Figure 1. Linear spring element for stage.

The main steps in the whole procedure of FEM analysis are shown in Fig. 2.

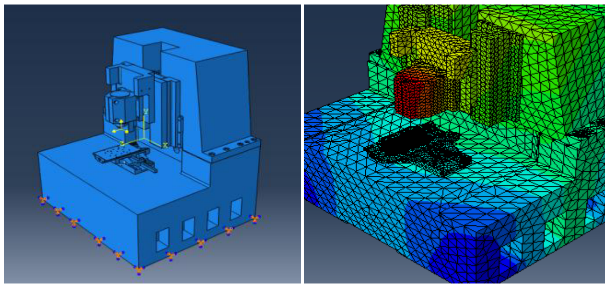
1) Modeling the 3D model of all the important component of the machine;
2) Define the materials properties;
3) Mesh the model with C3D10M element (a 10 nodes quadratic tetrahedron);
4) Define load and boundary condition;
5) Solve, and read the results;
6) Improve the structure if necessary.



(a) 3D virtual model (b) Simplified geometric model



(c) FEM model (d) Define analysis step



(e) Boundary and load condition (f) Result of analysis

Figure 2. The main procedure for FEM analysis.

4 Modal analysis

Modal analysis can obtain the fundamental vibration mode shapes and corresponding frequencies of the machine tool. Lanzosalgorithm in Abaqus for solving eigenvalue has the most general capabilities and high speed. In this paper, lanczos algorithm is selected to extract the first 60 natural frequencies of the machine tool.

The total effective mass of the model is 1.165T, the excited effective mass in x, y, z directions of the first 60 modes are 1.0625T, 1.0587T, and 1.0733T respectively. The proportion of the effective mass of x, y, z direction in total effective mass is 91.2%, 90.8%, 92.1%. It can be considered enough modal frequencies are extracted [7]. The first 60 natural frequencies of the machine tool are listed as below:

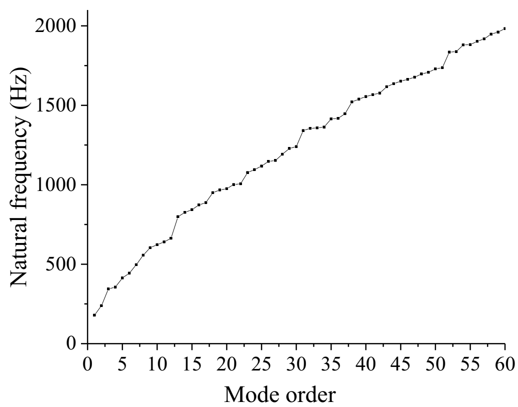


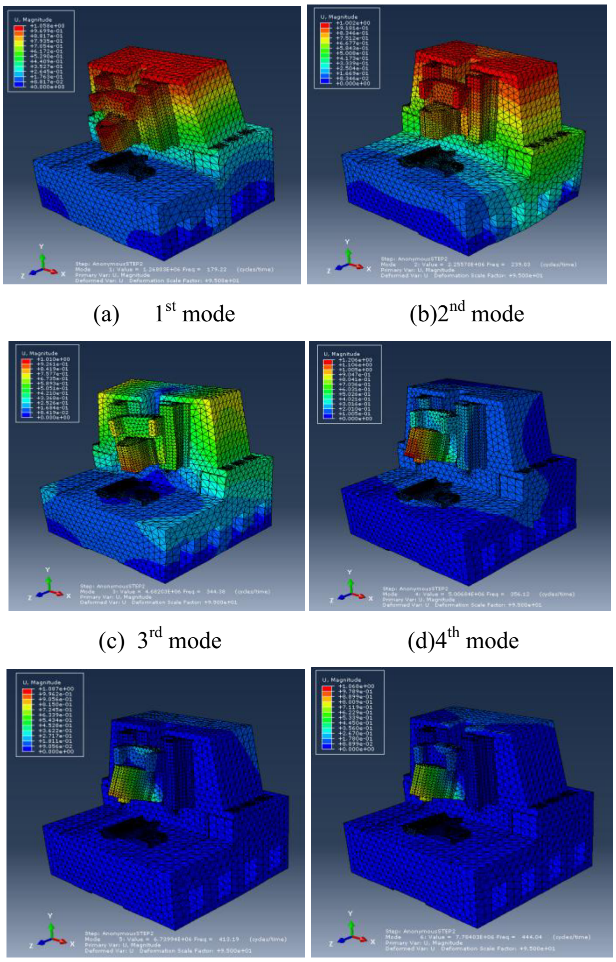
Figure 3. First 60 mode of the machine tool

Table 1 lists the first 10 natural frequencies and the description of the mode for the micro grinding machine tool. Higher order vibration shapes (7th to 10th mode) are considered as combined shapes and are hard to describe.

Table 1. First 10 natural frequencies of the micro grinding machine tool

No.	Mode	Frequency(Hz)
1	Column bending	179
2	Column rolling	239
3	Column twisting	344
4	Z slide bending	356
5	Z slide rolling	413
6	Z slide pitch	444
7	Complex vibration shapes	497
8	Complex vibration shapes	557
9	Complex vibration shapes	604
10	Complex vibration shapes	623

Detailed pictorial descriptions of first 6 natural frequencies and vibration modes are showed in Fig. 3.



(a) 1 st mode (b)2nd mode

(c) 3rd mode (d)4th mode

(e)5th mode (f)6th mode

Figure 3. First 6 natural frequencies and their mode.

The excited effectivemass of each mode is listed in Fig. 4.

It can be found the 2nd,5th,10thand 13th mode are main vibration mode ,the excited mass which corresponds to these mode is much more than other modals excited.

The 2nd mode has the most extracted mass, its corresponding frequency is 239Hz.The 5th mode has the second most extracted mass, its corresponding frequency is 413Hz. The mass extracted by the other mode are much less than the 2nd and 5th mode. It can be considered they have the most influence on dynamic behavior. Figure 3 (b) shows the 2nd mode of the machine tool, and figure 3 (e) shows the 5th mode of the machine tool. With the deformation of column, the displacement of spindle isobviously large, and therefore the column is the weak part in the machine tool configuration. It should be paid more attention to improve the structure of column, which could be achieved by increasing the thickness of the column or mounting bolts in the back of the column.

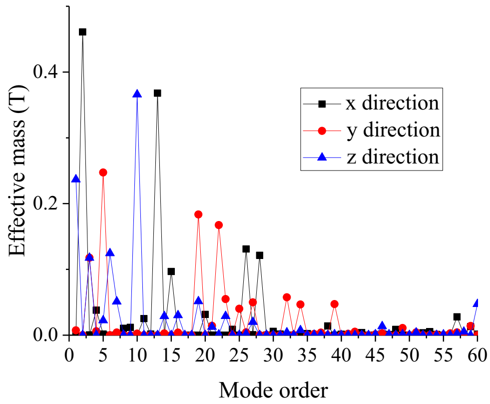


Figure 4. Excited effective mass.

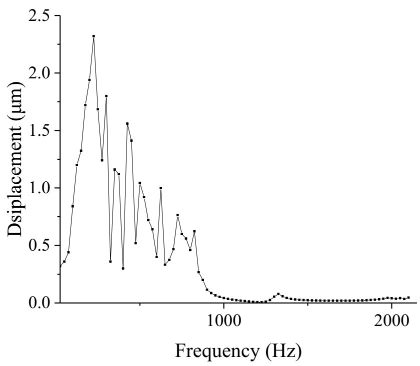
The first natural frequency has been recognized it should be higher than the machine operation frequency in the design of conventional precision machine, for example, the spindle rotational frequency. However, this principle cannot be used in the design of miniaturized ultra-precision micro grinding machine tool, because the maximum spindle speed of the micro grinding machine tool can be up to 2000 Hz (120,000 rpm). Modal analysis results provide a frequency selection guide for machine operation rather than a threshold for maximum spindle speed[8].

5 Harmonic response analysis

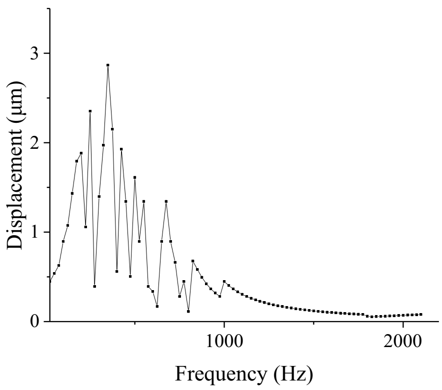
When the natural frequencies and their modes of vibration are obtained, harmonic response analyses were performed to determine the steady-state response of the machine to loads that vary harmonically with time. The harmonic response analysis verify whether or not the structure is able to overcome resonance and harmful effects caused by forced vibrations.

In this analysis, the machine structure was excited by a series of harmonic forces acting between work piece and cutting tool. To analysis the dynamic response of the cutting tool under heavy load, 5N force in 3 directions is applied to cutting tool. Frequency sweep range is set to 25-2100Hzwith 25 Hz intervals, it covers the main frequency range of the structure.Figure5.(a)-(c) show the harmonic response of relative displacement in 3 directions respectively.

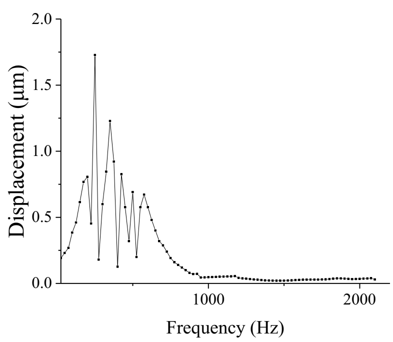
The maximum dynamic response displacement of about 2.8μm(y direction) occurs at 350Hz, which corresponds to a dynamic loop stiffness of 1.78N/μm. In the actual operation frequency range(1200- 2000 Hz), the dynamic displacement in 3 directions is much less than 0.5μm, and the dynamic loop stiffness is higher than 10N/μm. It can be considered the machine occurs few reasonce when machining.



(a)x direction



(b)y direction



(c) z direction

Figure 5. Harmonic response of micro grinding machine tool

6 Conclusion

A series of simulations were performed on the miniaturized ultra-precision micro grinding machine tool, including modal analysis and harmonic analyses. The simulations based on FEM are used as a powerful and effective tool for supporting the full design process in an iterative manner, which also enable the machine design to be optimized efficiently and effectively.

1) The first 60 mode were extracted, the excited effective mass in 3 directions are obtained, and the main vibration shape in x, y,z directions were found.
2) The cutting tool was applied with force to simulate the harmonic response of displacement, and the response curve was obtained. The max displacement is 2.38μm which occurs at 350Hz.In the actual operation frequency range, the machine tool is hardly to occur reasonce.

This work contributes to the development of a vertical miniaturized ultra-precision micro grinding machine tool. Simulation method is mainly used in this work. Therefore, the physical experiments are needed to verify the results after building the prototype machine.

Acknowledgement

This research was supported byNational Science andTech nology Major Project of the Ministry of Science and Tech nology of China (2013ZX04001-141).

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