Design and Analysis of a New Type of Three-Dimensional Ultrasonic Elliptical Vibration Tool Holder

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Abstract

This paper reports the innovative design of three-degree-of-freedom ultrasonic elliptical vibration tool holder (3-DOF UEVTH) based on coupled resonance mode. Ultrasonic elliptical vibration cutting technology is a kind of ultra-precision machining technology developed in recent years, and the structure design of its machining device is one of the difficulties in the current research. By analyzing the existing ultrasonic elliptical vibration cutting devices, a new three-dimensional ultrasonic elliptical vibration tool holder based on piezoelectric transducer is designed, and the modal analysis of the three-dimensional ultrasonic elliptical vibration tool holder is carried out by using the finite element analysis tool. it is determined that it has longitudinal vibration mode and bending vibration mode, and the resonance frequency of longitudinal vibration is very close to that of bending vibration by harmonic response analysis, which verifies the feasibility of the design.

Keywords

Three-Dimensional; Ultrasonic Elliptical Vibration; Design.

1. Introduction

Hard and brittle materials such as cemented carbide and stainless steel are widely used in aerospace, medical and communication technology and other high-tech fields because of their unique optical properties. However, because of the high hardness and low fracture toughness of these hard and brittle materials, it is easy to cause cracks and pits on the machined surface of brittle materials processed by traditional cutting methods. Therefore, in the 1950s, the Japanese scholar Kumabe J[1] put forward the one-dimensional ultrasonic vibration-assisted machining technology, which can effectively reduce the cutting force and increase the critical cutting depth in the ductile region of brittle materials. improve surface machining quality[2]. However, this machining method will cause high-frequency friction between the flank of the tool and the surface of the workpiece, resulting in the collapse of the tool tip[3]. In the 1990s, Shamoto[4]put forward the ultrasonic elliptical vibration cutting technology on the basis of one-dimensional vibration-assisted cutting, which improved the edge collapse phenomenon in the vibration machining process, further reduced the cutting force, and achieved good machining results, which has been widely concerned by scholars at home and abroad. Moriwaki et al.[5]put the piezoelectric ceramic plates at the upper and lower ends and the front and rear ends of the transducer respectively, and realize the elliptical vibration of the tool tip by applying sinusoidal alternating current to the two groups of piezoelectric plates respectively. The device is shown in figure 1 (a). Suzuki et al.[6]assembled piezoelectric ceramics, rear cover plate and horn in a sandwich manner to develop the world's first industrial UEVC device, whose structure is shown in figure 1 (b). Zhou et al.[7]use semicircular and circular piezoelectric ceramic pieces to realize the elliptical vibration of the tool tip, the semicircular piezoelectric ceramic piece can produce vibration in the bending direction under excitation, and the circular piezoelectric ceramic piece can produce longitudinal vibration under excitation, and its device structure is shown in figure 1 (c). The above

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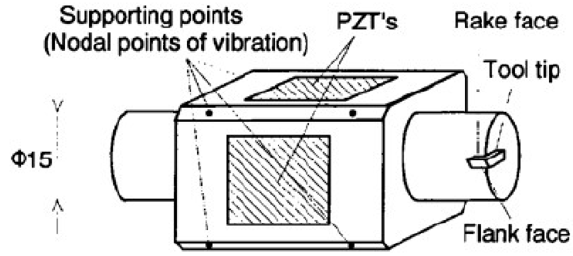
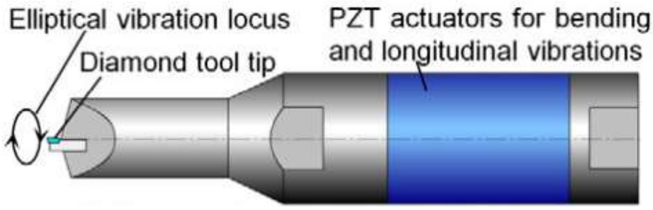
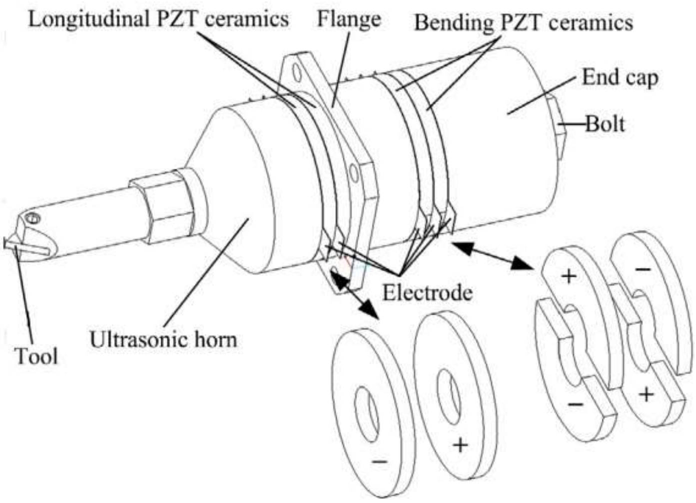
are two-dimensional ultrasonic elliptical vibration cutting devices, and the elliptical vibration cutting direction can not be changed with the machining demand, therefore, the purpose of this paper is to design a three-dimensional ultrasonic elliptical vibration tool holder which can change the cutting direction of elliptical vibration according to the machining requirements.



(a) the design of Moriwaki, etc.



(b) the design of Suzuki, etc.



(c) the design of Zhou, etc.

Figure 1. Existing UEVC devices

This paper firstly completes the structure design of the three-dimensional ultrasonic elliptical vibration tool holder. Through modal analysis, one longitudinal vibration mode and two bending vibration modes are determined, and the resonance frequency is determined through harmonic response analysis, which verifies the feasibility of the design.

2. Ultrasonic Elliptical Vibration Cutting Mechanism

The principle of ultrasonic elliptical vibration assisted cutting is mainly to make the tool tip of the tool follow the expected elliptical motion trajectory to remove material through the vibration assist device, as shown in Figure 2.

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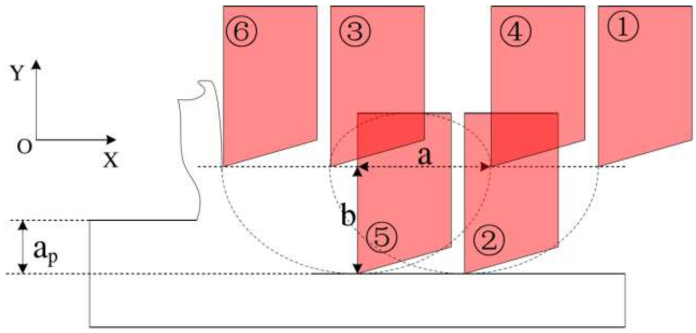

Figure 2. Principle diagram of ultrasonic elliptical vibration cutting

The most prominent characteristics of ultrasonic elliptical vibration assisted cutting are the characteristics of tool-chip separation and friction reversal in the machining process. As shown in figure 2, ①-⑥ is the position of the tool at different times. The trajectory of the tool in the X direction and Y direction is:

$$\begin{aligned} x &= a\cos(2\pi ft) \\ y &= b\sin(2\pi ft + \varphi) \end{aligned} \tag{1}$$

Where a and b is the amplitude of X and Y directions respectively, f is the vibration frequency of the tool, and φ is the phase angle.

The tool path in X direction and Y direction synthesizes to form an ellipse track with major and short axes as amemb, and the friction force of the tool is reversed during ②-③ and ⑤-⑥. In the cutting process, when the tool is separated from the chip, the conditions need to be met:

$$v_t > 2\pi fa \tag{2}$$

Where vt is the cutting speed.

3. Three-Dimensional Ultrasonic Elliptical Vibration Tool Holder

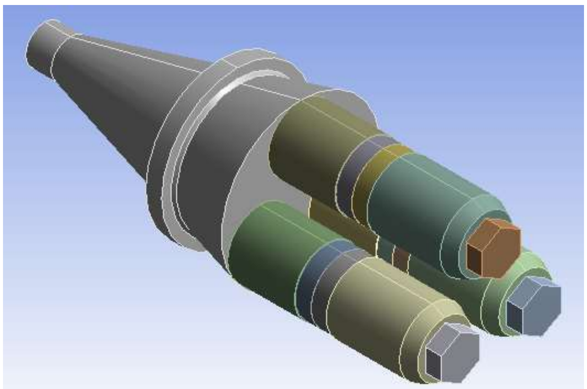

Figure 3. Three-dimensional ultrasonic elliptical vibration tool holder

The three-dimensional structure model of the three-dimensional ultrasonic elliptical vibration tool holder is shown in figure 3, which is composed of a horn and three piezoelectric transducers. When the flange on the horn is clamped at work, when the in-phase excitation is applied to three piezoelectric transducers at the same time, the horn will produce longitudinal vibration, and when the out-of-phase excitation is applied to two of the piezoelectric transducers at the same time, the horn will produce bending vibration. the combination of longitudinal vibration and bending vibration produces elliptical vibration at the output end of the horn.

4. Finite Element Analysis

4.1 Establishment of Finite Element Model

In this paper, the material of piezoelectric ceramics is PZT-8, the outer diameter is 20mm, the inner diameter is 10mm, the thickness is 5mm, and the number is 6. Because the thickness of the electrode is very small, it is chosen to ignore it in modeling. The horn and front cover plate are made of 2Al2, and the rear cover plate and pre-tightening bolts are made of 45 steel. Table 1 shows the material parameters of the three-dimensional ultrasonic elliptical vibration tool holder.

Table 1. Material parameters of ultra-precision tool holder with resonant ultrasonic elliptical vibration

Materials	Density(kg/m^3)	Young's modulus(GPa)	Poisson's ratio
C45	7800	210	0.3
PZT-8	7600	66	0.32
2Al2	2730	69	0.34

After the material definition is completed, the meshing is carried out, and the whole model is meshed with the constrained flange circumferential surface as the boundary condition. The meshing adopts the adaptive meshing technology. Considering the convergence and computational efficiency of the results, the mesh quality is set to medium, the element size is set to 2.5mm, and the total number of nodes and elements is 40722 and 14645 respectively. The finite element model is shown in figure 4.

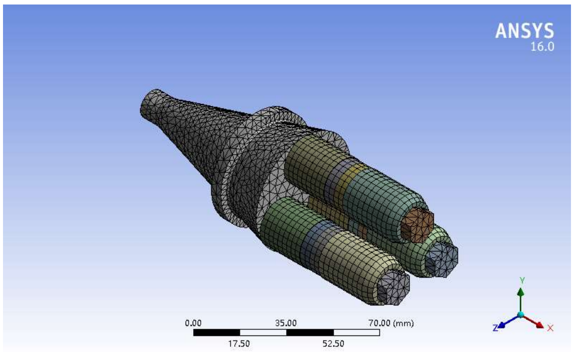

Figure 4. Finite element model of three-dimensional ultrasonic elliptical vibration tool holder

4.2 Modal Analysis

In order to determine the natural frequency and vibration mode of the three-dimensional ultrasonic elliptical vibration tool holder, the modal analysis of the tool holder model was carried out. Ignoring the influence of bolt pre-tightening force, the contact type between components is set to Bonded, the boundary condition is set to fixed flange circumferential surface, the solution method is blocklanczos, and the solution range is 20~25kHz. The obtained vibration mode cloud diagram is shown in figure 5, in which figure 5 (a) is a fourth-order bending vibration mode with a vibration frequency of 23307Hz, figure 5 (b) is a fifth-order bending vibration mode with a vibration frequency of 23308Hz, and figure 5 (c) is a sixth-order longitudinal vibration mode with a vibration frequency of 23366Hz.

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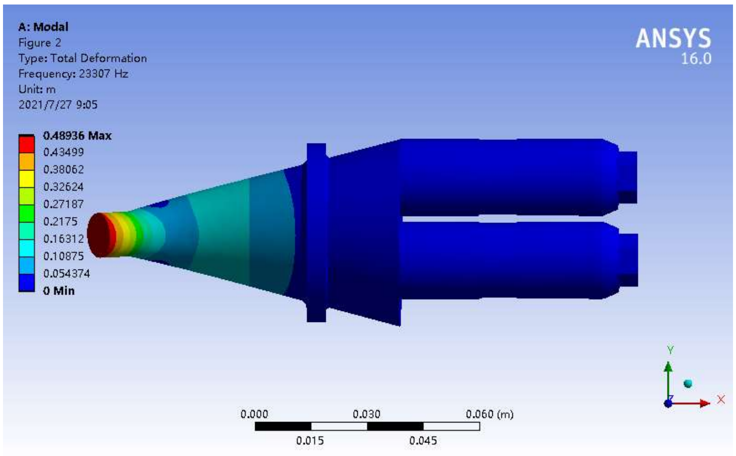
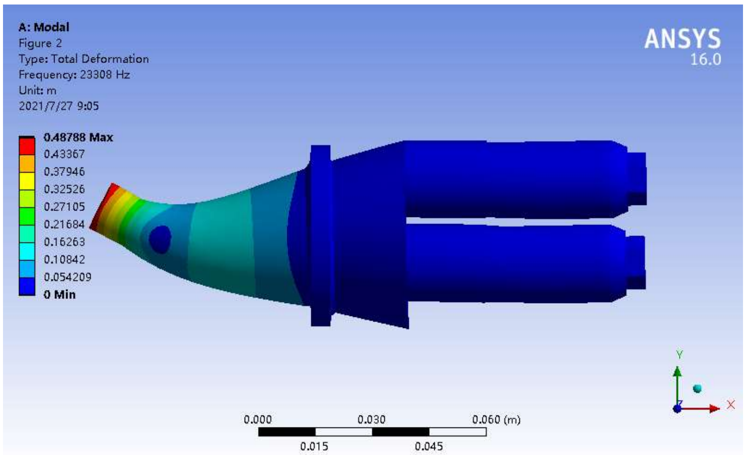
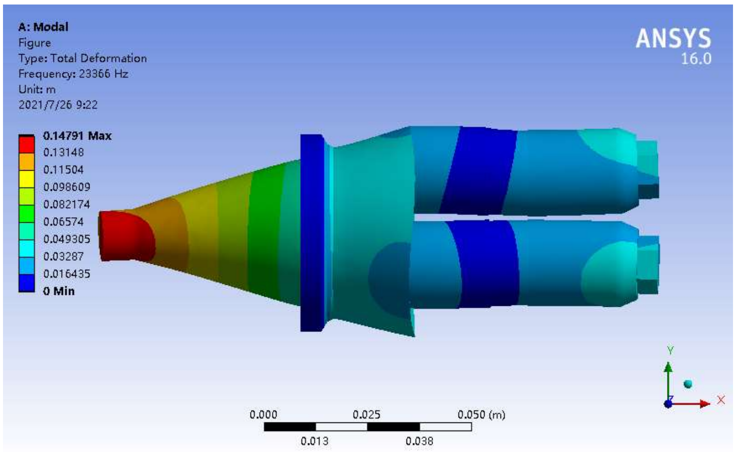


(a) 4-th bending vibration mode



(b) 5-th bending vibration mode



(c) 6-th longitudinal vibration mode

Figure 5. Vibration modal cloud diagram

4.3 Harmonic Response Analysis

Harmonic response analysis is used to determine the steady-state response of three-dimensional ultrasonic elliptical vibration tool holder under harmonic loads with known frequencies and amplitudes. In the harmonic response analysis, the input force with an amplitude of 1N for each

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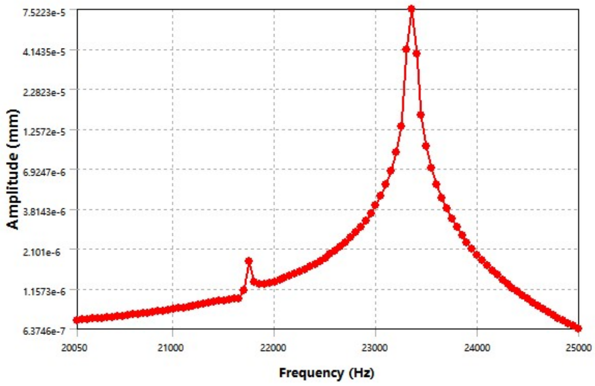
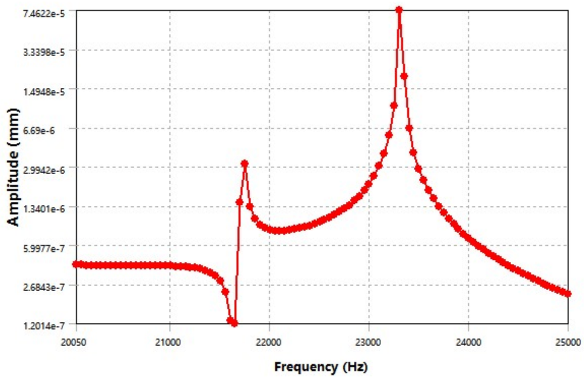
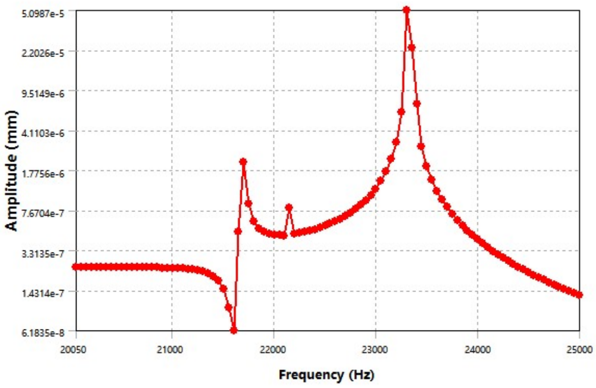
piezoelectric ceramic is given, and the amplitude-frequency response curve of the particle at the front end of the three-dimensional ultrasonic elliptical vibration tool holder is obtained by frequency sweep analysis in the 20~25kHz frequency range, as shown in figure 6. Figs. 6 (a), (b) and (c) represent the amplitude-frequency response curves in the direction of x (longitudinal), y (bending) and z (bending) respectively. It can be found that the resonant frequency of longitudinal vibration is 23350Hz, the resonant frequencies of both bending vibration are 23300Hz, and the resonant frequencies of longitudinal and bending vibration are close to the same, indicating that the structural design of the tool holder is reasonable.



(a) x-direction



(b) y-direction



(c) z-direction

Figure 6. Amplitude-frequency response curve

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5. Conclusion

In this paper, a new type of three-dimensional ultrasonic elliptical vibration tool holder is proposed, and the finite element model of the tool holder is established and the dynamic simulation analysis is carried out, including modal analysis and response analysis. the results of dynamic analysis show that the three-dimensional ultrasonic elliptical vibration tool holder has the conditions to produce elliptical vibration, and the feasibility of the design is verified.

References

[1] Kumabe J. Precision Machining Vibration cutting: Foundation and Application [M]. Beijing: machinery Industry Press, 1985.

[2] Moriwaki T,Shamoto E.Ultraprecision diamond turning of stainless steel by applying ultrasonic vibration[J].CIRP Annals:Manufacturing Technology,1991,40(1):559-562.

[3] Jin M,Murakawa M.Development of a practical ultrasonic vibration cutting tool system[J].Journal of materials Processing Technology,2001,113(1/2/3):342-347.

[4] Shamoto E,Moriwaki T.Study on ultrasonic cutting[J].CIRP Annals:Manufacturing Technology,1994, 43(1):35-38.

[5] Moriwaki T,Shamoto E.Ultrasonic vibration cutting[J].CIRP Annals:Manufacturing Technology,1995, 44(1):31-34.

[6] Suzuki N,Haritani M,Yang J,et al.Elliptical vibration cutting of tungsten alloy molds for optical glass parts[J]. CIRP Annals:Manufacturing Technology,2007,56(1):127-130.

[7] Zhou M,Hu L.Development of an innovative device for ultrasonic elliptical vibration cutting[J]. Ultrasonics,2015,60:76.