IOP Conference Series: Earth and Environmental Science

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To cite this article: Sheng Lin and Xubiao Deng 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **267** 052044

IOP Conf. Series: Earth and Environmental Science **267** (2019) 052044 doi:10.1088/1755-1315/267/5/052044

# Three-dimensional elliptical vibration cutting device based on the curved beam

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**Abstract.** A novel three-dimensional elliptical vibration cutting device is proposed based on curved beams. Arc curved beam compliant element is employed to synthesize the structure. Static analysis and modal analysis are carried out on the micro-displacement stage. Results show that the maximum stress applied to the device in all three directions is less than the allowable stress. And the first natural frequency of the device is relatively high. The output of the three-dimensional elliptical trajectory is simulated, which meets the requirement.

## 1. Introduction

With the development of manufacturing, more and more attention has been paid to difficult-to-cut materials such as hardened steel and silicon carbide. However, the traditional cutting method has poor processing properties to the above materials, which leads to cutting-tool wear, deterioration of the surface quality and reduction of machining accuracy [1]. In order to solve this series of problems, the elliptic vibration cutting theory was proposed by Japanese scholars in the 1990s. Elliptical vibration cutting has many advantages such as suppression of tool wear, improving surface processing quality, and improving machining accuracy. These advantages have attracted many scholars to research on the technology of elliptical vibration cutting [2,3]. At present, the elliptical vibration cutting device is divided into resonant type and non-resonant type. The low frequency state of piezoelectricity to excite the high-frequency resonance state of the transducer for resonant elliptical vibration cutting device. The tool is driven by the transducer and the working frequency is above 20 KHz. Compared with the resonance type, the non-resonant elliptical vibration cutting device has a lower working frequency. Moreover, the trajectory parameters of the three-dimensional elliptic motion can be independently controlled, which can adapt to different cutting conditions. Kim[4] designed a programable non-resonant elliptical vibration cutting device, which can improve the cutting quality. Wang and Liu[5-6] proposed a decoupled three dimensional elliptical vibration cutting device, which effectively avoids the motion coupling. However, the existing non-resonant elliptical vibration cutting devices have complex structures and are difficult to process.

Here, we design a parallel elliptical vibration cutting device based on curved beam, which can not only realize the movement of three directions, but also has simple structure and convenient processing. The static and dynamics analysis of the device is carried out, the maximum stress of the device in three directions is less than the allowable stress and the first order natural frequency is high, which effectively avoids the resonance phenomenon, and the trajectory of elliptic motion is simulated.

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## 2. Design of elliptical vibration cutting device

Figure. 1 shows the structure of the 3-D elliptical vibration cutting device based on the space curved. The device consists of three piezoelectric ceramic promoters arranged vertically with each other, four same circular curved beam compliant units, micro-displacement stage, matrix, connecting plate, backplane, base, head cover, fixture, diamond tool, multiple set screws, bolts, and nuts. The micro-displacement stage is driven directly by three piezoelectric ceramic actuators, which causes any elliptical motion in the space at the cutter point of the diamond tool. The piezoelectric ceramic accelerators in three directions are pre-tightened by pre-tightening bolts along their respective axes, and the bolt pre-tightening process is independent of each other.

The most important part of the device is the micro-displacement stage with the curved beam compliant mechanism as the tool carrier, as shown in Figure 2. The stage is connected with the base through four curved beam flexible elements.

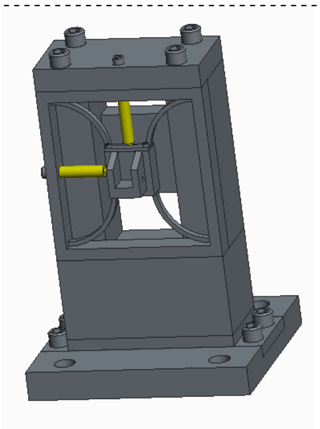

Figure 1 Three-dimensional elliptical vibration cutting device

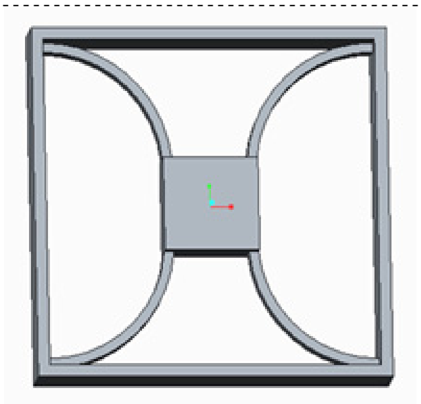

Figure 2 Micro-displacement structure

## 3. Finite element analysis of the device

We conduct the static analysis of micro-displacement stage. The geometry model is imported into the ANSYS workbench. The material is set as aluminium alloy. Its material properties are: density 2770 kg/m3, elastic modulus 71 GPa, Poisson's ratio 0.33. The maximum deformation and equivalent stress nephograms in X, Y and Z directions of micro-displacement stage is obtained by applying 700N concentrated load in X, Y and Z directions respectively, as shown in Figure 3.

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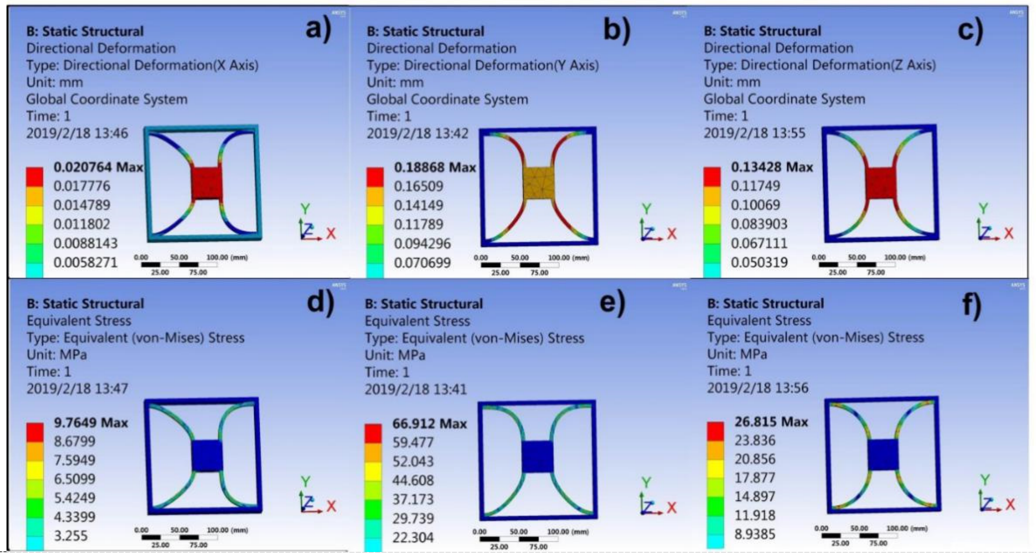


Figure 3. a), b), c), e), d), f) correspond to the maximum deformation and equivalent stress nephograms in X, Y and Z directions.

Figure. 3 shows that the equivalent stress of the micro-displacement stage is mainly concentrated at the joint of the bending beam element and the stage. The maximum stress in the X direction is 9.6837 MPa, the maximum stress in the Y direction is 9.6354 MPa, and the maximum stress in the Z direction is 27.063 MPa, The maximum stress in three directions is less than the allowable stress of aluminum alloy. And the curved beam compliant element can achieve micro-displacement deformation. Modal analysis of the curved beam micro-displacement stage is carried out, and the first six modes of vibration is shown in Figure 4. The natural frequencies are shown in Table 1.

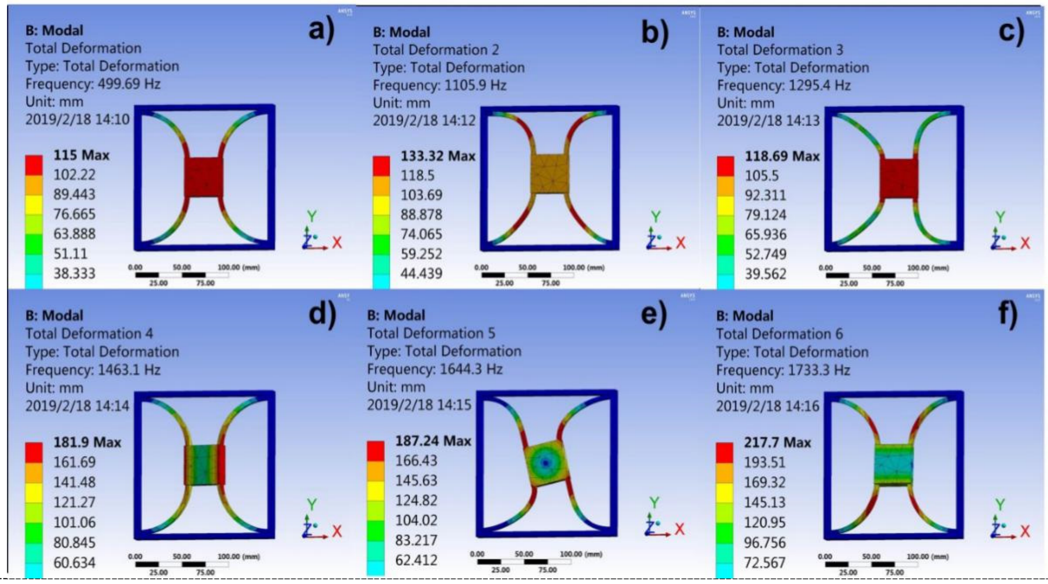


Figure 4. a), first order mode; b), second order mode; c), third order mode; d), fourth order mode; e), fifth order mode; f), sixth order mode;

Table 1. The first six order vibration frequencies of the model

| first-order frequency | second-order frequency | third-order frequency | fourth-order frequency | fifth-order frequency | fifth-order frequency |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 499.69Hz | 1105.9Hz | 1295.4Hz | 1463.1Hz | 1644.3Hz | 1733.3Hz |

The first mode is that the micro-displacement stage moves along the Z-axis, the second mode is that the micro-displacement stage moves along the Y-axis, the third mode is that the micro-displacement stage moves along the X-axis. The first three modes of the curved beam micro-displacement stage just satisfy the required three translations. The frequency of the first mode is 499.69Hz, and the natural frequency is relatively high, which effectively avoids the resonance phenomenon and meets the design requirements.

## 4. Analysis of 3-D elliptical vibration trajectory

3-D elliptical vibration cutting principle is that spatial elliptical trajectory is obtained at the cutter point of the diamond tool by the piezoelectric stacking reactor or other actuators. And the projections of the spatial ellipse on the three coordinate planes are three plane ellipses or two plane ellipses and one line. The driving signals applied to the X, Y and Z directions of the middle micro-displacement stage are set as follow,

$$\begin{cases} \boldsymbol{F_x(t) = v_x \cos(2\pi f t + \alpha)} \\ \boldsymbol{F_y(t) = v_y \cos(2\pi f t + \beta)} \\ \boldsymbol{F_z(t) = v_z \cos(2\pi f t + \gamma)} \end{cases} \tag{1}$$

where, $F_x(t)$, $F_y(t)$ and $F_z(t)$ are the input force; $v_x$, $v_y$ and $v_z$ are the amplitudes of $F_x(t)$, $F_y(t)$ and $F_z(t)$; $\alpha$, $\beta$ and $\gamma$ are the initial phases, and $f$ is the frequency.

The output displacement of the contact point between workpiece and tool tip can be expressed as [8]

$$\begin{cases} x(t) = A_x \cos(2\pi f t + \lambda) - v_c \cos\varphi \\ y(t) = A_y \cos(2\pi f t + \omega) \\ z(t) = A_z \cos(2\pi f t + \theta) - v_c \cos\varphi \end{cases} \tag{2}$$

where, $A_x$, $A_y$ and $A_z$ are the amplitudes of driving signals $\mathrm{x}(t)$, $\mathrm{y}(t)$ and $\mathrm{z}(t)$; $\lambda$, $\omega$ and $\theta$ are the initial phases of driving signals, and $f$ is the frequency of driving signals, $v_c$ is the cutting speed , φ is the angle between the cutting direction and the three-dimensional elliptical plane.

The driving signals of three piezoelectric ceramic actuators are simultaneously adjusted, the tool tip trajectory can be synthesized into a three-dimensional ellipse. When $A_x, A_y$, $A_z$ are equal to 10, $\lambda$ equals 0, $\omega$ equals pi/4, $\theta$ equals pi/2, $f$ equals 150 Hz, $v_c$ equals 3μm / s, $\varphi$ equals pi/4. Matlab software is used for trajectory calculation, the obtained 3-D elliptical vibration elliptical trajectory is shown in Figure 5.

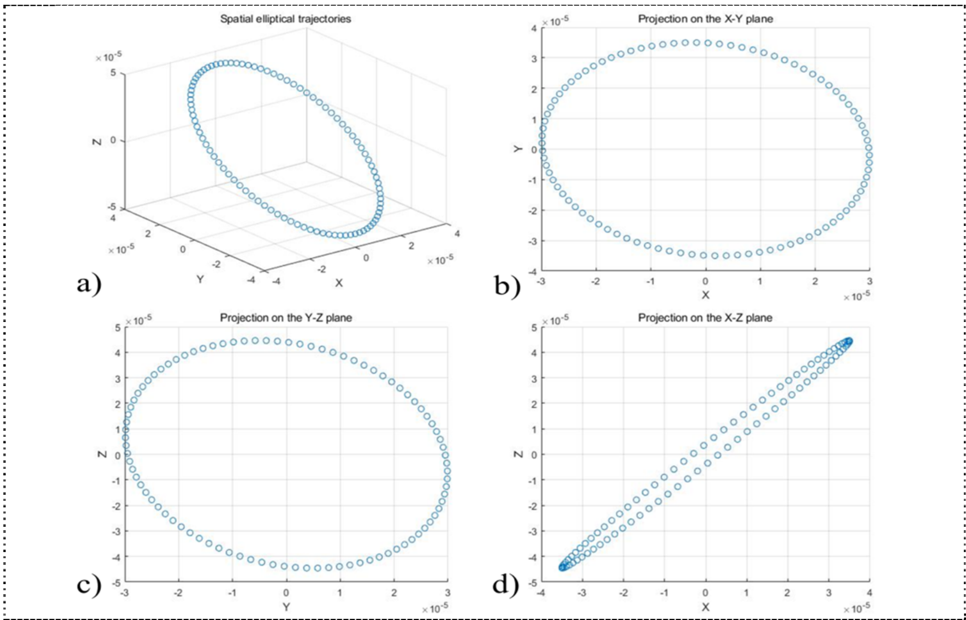


Figure 5. a),Spatial elliptical trajectories. b), Projection on the X-Y plane. c), Projection on the X-Z plane. d), Projection on the Y-Z plane.

## 5. Conclusions

A three-dimensional elliptical vibration cutting device based on the curved beam is proposed. Static analysis of the micro-displacement stage is carried out, and results show that the maximum stress is less than the allowable stress. Modal analysis demonstrated that the first-order natural frequency of the device is 499.69Hz, which is relatively high. The principle of the 3-D elliptical trajectory is presented. And simulation results show that the output 3-D elliptical trajectory of the vibration cutting device meets the requirement. The design method of the 3-D elliptical vibration cutting device can present important reference for the design of this kind of cutting device.

## Acknowledgments

This work is supported by National Natural Science Foundation of China (Grant no. 51775078 )

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