Development of an optimized smart tool holder using symmetrical structure for three axis cutting force measurement in diamond cutting

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Cutting force measurement is an important technique to monitor machining process in diamond cutting. This paper presents an optimized smart tool holder using symmetrical structure of a fast tool servo (FTS) for three axis cutting force measurement by utilizing six piezoelectric force sensors. The cutting force in each axis is measured by using the differential result of two sensors for eliminate influence of environment noise, bias current and temperature drift. An improved algorithm that is combination of differential and dynamic accumulation method is developed for stable and accurate static force measurement. Tests are carried out to verify the effectiveness of the algorithm on improvement of stability and accuracy of output voltage and static force measurement, which demonstrates that the influence of environment noise, bias current and temperature drift can be reduced effectively. Then, the smart tool holder is integrated on a FTS for cutting experiments. By compared with commercial dynamometer, it is verified that the proposed tool holder system has excellent performance of high sensitivity and high accuracy in three axis cutting force measurement.

1. Introduction

Single point diamond cutting with utilizing a fast tool servo (FTS) is an important technique for fabrication of structured and freeform surfaces with nanometric roughness [1]. For high accurate machined surface, cutting status such as tool wear and surface micro defects need to be monitored during cutting process [2]. Due to including rich information of interface between the tool and the workpiece, cutting force is a significant factor that can be in-process measured for reflecting cutting status [3].

In recent years, many researches of in-process cutting force measurement in diamond cutting have been studied. Strain gauge is a common type force sensor, but strain gauge has a low sensitivity that is unsuitable to measure force in nanometric cutting [4]. Measuring elastic deformation of flexible structure by displacement sensor is an indirect force measurement method [5], but the rigidity and bandwidth of cutting system would be low, which limit the efficiency and size of cutting. With high rigidity and sensitivity, piezoelectric force sensor is preferred to measure cutting force in nanometric cutting [6]. However, as general, it is difficult for the piezoelectric force sensor to measure static force due to the signal decay of the charge amplifier that is caused by charge leakage [7].

This paper presents an optimized smart tool holder using symmetrical structure of a FTS for three axis cutting force measurement by utilizing six piezoelectric force sensors. An improved algorithm that is combination of differential and dynamic accumulation method is developed for stable and accurate static force measurement. Tests are carried out to verify the effectiveness of the algorithm on improvement of stability and accuracy of output voltage and static force measurement, which demonstrates that the influence of environment noise, bias current and temperature drift can be reduced effectively. Then, the smart tool holder is integrated on a FTS for cutting experiments to demonstrate the sensitivity and accuracy of three axis cutting force measurement.

2. Principle and structure design

The previous works of authors have presented a tool holder for three axis force measurement by utilizing three piezoelectric force sensors with orthogonal distribution, and developed a quasi-static force measurement algorithm based on the concept of dynamic accumulation [8]. Fig. 1 shows the schedule of three axis force measurement in diamond cutting. When received a three dimensional force, piezoelectric force sensors generate charge signal based on piezoelectric effect, then the charge signal is amplified by charge amplifier and processed by quasi-static force measurement algorithm to output measured force signals. As shown in Fig. 1, the force measurement result is interfered obviously by the bias current of the charge amplifier and the temperature drift, which need to be considered carefully for accurate force measurement.

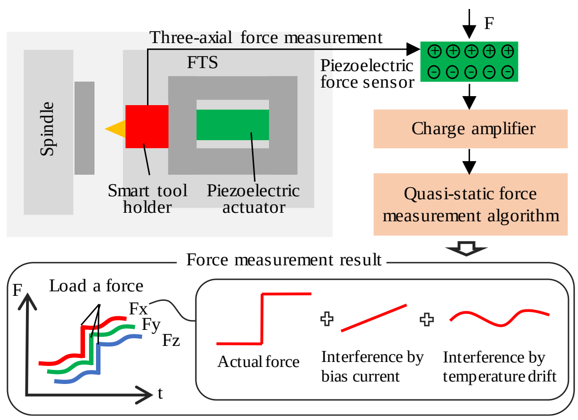

Fig. 1 Schedule of three axis force measurement in diamond cutting.

Differential method has been proved an effective method to reduce these interferences [9]. To improve three axis force measurement accuracy, a novel smart tool holder based on differential method is developed in this paper. Fig. 2 shows the structure of the smart tool holder and principle of three axis force measurement based on differential method. The smart tool holder is composed of a flexible hinge and six piezoelectric force sensors. There are two same sensors distributed symmetrically in X axis, and also two distributed symmetrically in Y axis. In addition, two sensors with different size are distributed in Z axis by the smaller sensor inside the bigger sensor. All the sensors have the same height of 1 mm. The sensors in X and Y axis have outside diameter of 12 mm and inside diameter of 8 mm, and the bigger sensor in Z axis has outside diameter of 20 mm and inside diameter of 12 mm as well as the smaller one has outside diameter of 8 mm and inside diameter of 3 mm. Thus, force in each axis is measured together by two sensors. The measured forces can be expressed as:

$$
\begin{aligned}
F_{x1}&=F_{x1\text{-}act.}+K_1*I_{bias}+K_2*T_{drift}\\
F_{x2}&=F_{x2\text{-}act.}+K_1*I_{bias}+K_2*T_{drift}\\
F_{y1}&=F_{y1\text{-}act.}+K_1*I_{bias}+K_2*T_{drift}\\
F_{y1}&=F_{y2\text{-}act}+K_1*I_{bias}+K_2*T_{drift}\\
F_{z1}&=F_{z1\text{-}act}+K_1*I_{bias}+K_2*T_{drift}\\
F_{z1}&=F_{z2\text{-}act}+K_1*I_{bias}+K_2*T_{drift}
\end{aligned}
\tag{1}
$$

Where F_{x1}, F_{x2}, F_{y1}, F_{y2}, F_{z1}, F_{z2} are direct measured results, $F_{x1\text{-}act.}$, $F_{x2\text{-}act}$, $F_{y1\text{-}act}$, $F_{y2\text{-}act}$, $F_{z1\text{-}act}$, $F_{z2\text{-}act}$ are actual force without interference. K_1 and K_2 are influence coefficient of the bias current of the charge amplifier and the temperature drift on measured results. Due to the same charge amplification circuit and working environment, the bias current I_{bias} and temperature drift T_{drift} are assumed to be same value of all six sensors. Thus, to eliminate influence of the bias current and temperature drift, the measured forces can be calculated by:

$$
\begin{aligned}
F_{x\text{-}meas}&=F_{x1}-F_{x2}=F_{x1\text{-}act}-F_{x2\text{-}act}\\
F_{y\text{-}meas}&=F_{y1}-F_{y2}=F_{y1\text{-}act}-F_{y2\text{-}act}\\
F_{z\text{-}meas}&=F_{z1}-F_{z2}=F_{z1\text{-}act}-F_{z2\text{-}act}
\end{aligned}
\tag{2}
$$

When the tool holder receives positive forces along three axial directions, $F_{x1\text{-}act}$, $F_{y1\text{-}act}$, $F_{z1\text{-}act}$ and $F_{z2\text{-}act}$ are positive values that represent pressure, and $F_{x2\text{-}act}$ and $F_{y2\text{-}act}$ are negative values that represent tension. Due to a bigger stressed area, $F_{z1\text{-}act.}$ has a bigger value than $F_{z2\text{-}act}$. Thus, $F_{x\text{-}meas}$ $F_{y\text{-}meas}$ and $F_{z\text{-}meas}$ can all be calculated to be effective values in this way.

3. Static force measurement tests

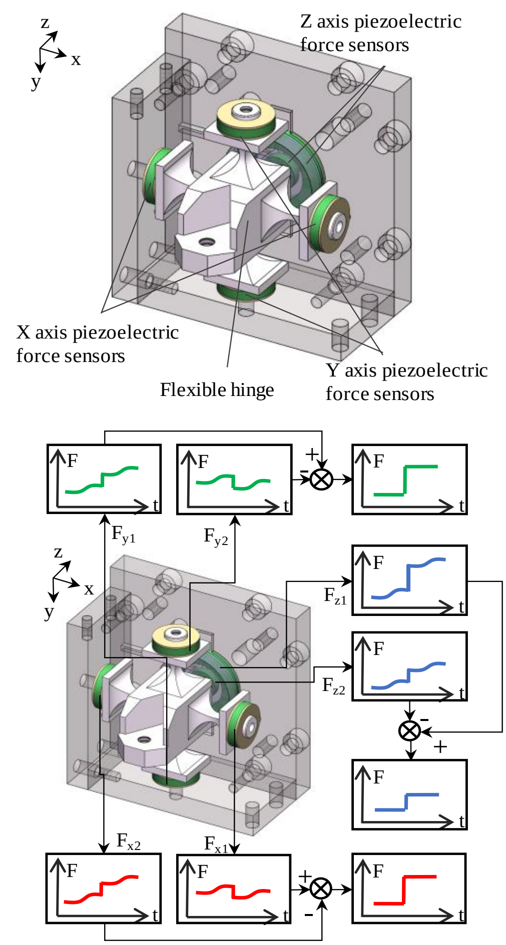

Fig. 2 structure of the smart tool holder and principle of three axis force measurement based on differential method.

In actual cutting process, there are not only cases that cutting force is dynamically changing, but only cases that cutting force is cutting force is static or quasi-static. Accurate static force measurement is important for reflect cutting status during static and quasi-static cutting process [8]. In this section, to improve the stability and accuracy of static force measurement, an improved algorithm that is combination of differential and dynamic accumulation method is developed and tested.

Fig. 3 shows the experiment setup for tests of the smart tool holder. A homemade six-channel charge amplifier with using precision amplifier chips (LMP7721) was designed for force measurement. When a piezoelectric force sensor receiving a constant force F, the output voltage from charge amplifier can be expressed as [9]:

$$u(t)=F\cdot d_{33}/C_F\cdot e^{-t/C_F R_F} \tag{3}$$

where d_{33} is piezoelectric coefficient, C_F and R_F are feedback capacitor and feedback resistance of the charge amplifier. In this paper, C_F and R_F are set to be 1 nF and 10 MΩ, respectively. As from Eq. (3), an

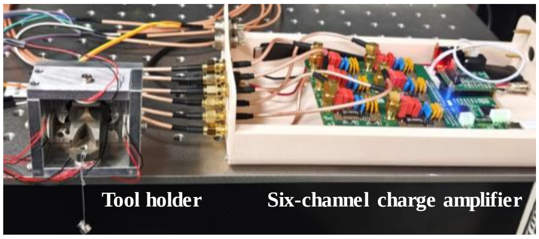

Fig. 3 Experiment setup for tests of the smart tool holder.

instantaneous voltage generates at the moment of receiving force and then gradually decay to near zero, and the initial voltage is linear to the force.

Experiments were conducted to calibrate the relationship of the instantaneous voltage and the constant force at the moment of load. A series of forces were load on the tool holder along X, Y and Z axis by using standard weight of 1-10 g. Based on the Eq. (2), the voltages in X, Y and Z axis are calculated to be:

$$\begin{aligned} u_{x\text{-}meas} &= u_{x1} - u_{x2} \\ u_{y\text{-}meas} &= u_{y1} - u_{y2} \\ u_{z\text{-}meas} &= u_{z1} - u_{z2} \end{aligned} \tag{4}$$

where u_{x1}, u_{x2}, u_{y1}, u_{y2}, u_{z1}, u_{z2} are output voltages of the sensors. Based on the calibration results of the instantaneous voltage and the constant force at the moment of load, when load different forces in X axis, there is a good linearity between measured voltage and force with a sensitivity of 1.35 mV/mN. Similarly, Y and Z axis have good linearity of force measurement with sensitivity of 1.92 mV/mN and 0.84 mV/mN. The couplings are also plotted in the figure. When load in X axis, couplings on Y axis and Z axis are 9.5 % and 14.5 %, respectively. When load in Y axis, couplings on X axis and Z axis are 2.3 % and 12.6 %, respectively. When load in Z axis, couplings on X axis and Y axis are 2.7 % and 13.4 %, respectively. The relationship of actual force and voltage can be expressed by using a coupling matrix K:

$$\begin{bmatrix} u_{x-meas} \\ u_{y-meas} \\ u_{z-meas} \end{bmatrix} = K \cdot \begin{bmatrix} f_{x-act} \\ f_{y-act} \\ f_{z-act} \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot \begin{bmatrix} f_{x-act} \\ f_{y-act} \\ f_{z-act} \end{bmatrix} \tag{5}$$

where $u_{meas}=[u_{x\text{-}meas}\ u_{y\text{-}meas}\ u_{z\text{-}meas}]^T$ is instantaneous voltage vector caused by constant force $f_{act.}=[f_{x\text{-}act}\ \ f_{y\text{-}act}\ \ f_{z\text{-}act.}]^T$ at the moment of load. Coupling matrix K can be calculated by input calibration data into Eq. (5). Thus, the force at the moment of load can be obtained by:

$$f_{act} = K^{-1} \cdot u_{meas} \tag{6}$$

For static force measurement, dynamic accumulation method is used to compensate for charge leakage [8]. The sampling time is set to T, and there is no force at moment of start sampling. With referring the difference of the force at iT compared to $(i\text{-}1)T$ as the change force at iT, the actual force at nT can be calculated to be sum of all change forces at previous moments. The change force $f_{act}(i)=[f_{x\text{-}act}(i) f_{y\text{-}act}(i) f_{z\text{-}act}(i)]^T$ at moment iT relative to the previous one can be expressed as :

$$f_{act}(i) = K^{-1} \cdot (u_{meas}(i) - u_{meas}(i-1) \cdot e^{-T/C_F R_F}) \tag{7}$$

where $u_{meas}(i)=[u_{x\text{-}meas}(i)\ u_{y\text{-}meas}(i)\ u_{z\text{-}meas}(i)]^T$ is voltage vector at moment iT. Thus, the actual force $F_{meas}(i)=[F_{x\text{-}meas}(i)\ F_{y\text{-}meas}(i)\ F_{z\text{-}meas}(i)]^T$ at moment nT can be expressed as:

$$F_{meas}(i) = \sum_{i=0}^{n} f_{act}(i) \tag{8}$$

With applied a force of 19.8 mN to X axis, the voltage and measured static force in X axis are plotted in Fig. 4. As shown from the voltage curves in Fig. 4 (a), the voltages rapidly change at the moment of load and then decay to initial status. The voltages u_{x1} and u_{x2} from the two force sensors in X axis have the synchronous and consistent signal fluctuate caused by environment noise and bias current. After differential calculation, the measured voltage $u_{x\text{-}meas}$ is smooth and stable with signal fluctuate being effectively eliminated. As seen from static force measurement results in Fig. 4 (b), the measured force F_{x1} and F_{x2} from the two force sensors have obvious signal fluctuate and incline that is influenced by environment noise and bias current respectively. With differential calculation, the measured force $F_{x\text{-}meas}$ is greatly coincident with actual load status of the tool holder with signal fluctuate and incline being eliminated. There is noise of only about 0.4 mN of the measured force $F_{x\text{-}meas}$, which is caused by the small difference of effect of environment noise on output voltage of the two sensors. Similarly, after differential calculation, the noise in Y and Z axis are only about 0.7 mN and 0.9 mN.

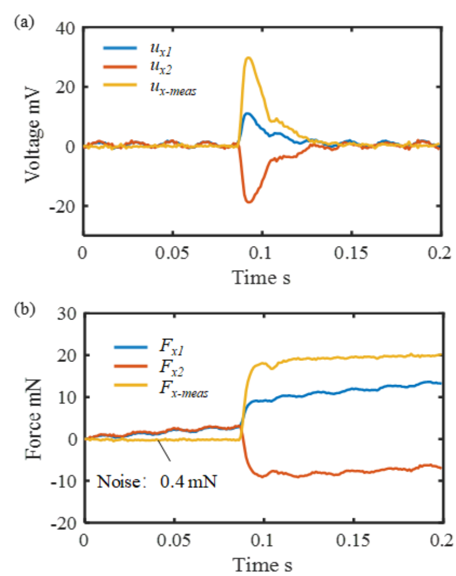

Fig. 4 (a) Voltage and (b) measured static force in X axis.

4. Cutting experiments and discussion

Cutting experiments were conducted to verify the capacity of the proposed smart tool holder for cutting force measurement. Fig. 5 shows the experiment setup. The smart tool holder was integrated on a FTS and then the FTS was mount on an ultra-precision five axis machine tool. The used single crystal diamond tool had nose radius of 1 mm and rake angle of 0°. To verify the accuracy of force measurement, a commercial dynamometer (9109AA, Kistler) was used to measure cutting force as reference results, and the copper workpiece is fixed on the dynamometer.

Curved microstructure arrays were fabricated to further verify the accuracy of three axis force measurement. The length of a microstructure unit along X and Y axis are both set to be 100 μm, and

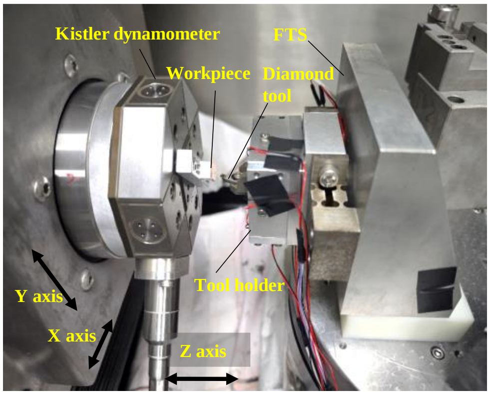

Fig. 5 Setup of cutting experiments.

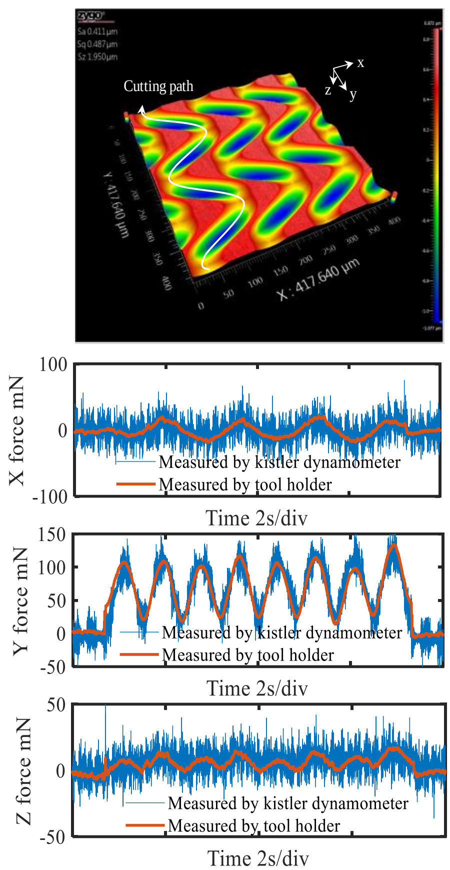

Fig. 6 Cutting result and cutting force of curved microstructure arrays.

the depth is set to be varied from 0.6 µm to 1.6 µm. The cutting result measured by a white-light interferometric microscope and the cutting forces of a group of curved microstructures in machining process are shown in Fig. 6. As can be seen in the figure, the cutting forces measured by tool holder have the same trend of change and the smaller noise compared with that measured by dynamometer. Especially of Z axis force, there is clear periodic feature of the force measured by the tool holder but not of that measured by dynamometer, which demonstrates high sensitivity of the proposed method. Cutting forces in three axes all have periodic features corresponding to the cutting of each microstructure unit, and Y axis force has a feature amplitude of about 100 mN, which is much larger than that of 15 mN in X axis and of 11 mN in Z axis.

5. Conclusion

This paper presents an optimized smart tool holder using symmetrical structure of a FTS for high stability and high accuracy of three axis force measurement. A novel smart tool holder based on symmetrical and flexible structure with utilizing six piezoelectric force sensors had been designed and developed, which high force measurement sensitivity of more than 0.84 mV/mN. An improved algorithm that is combination of differential and dynamic accumulation method is developed for stable and accurate static force measurement. Based on the algorithm, it had been verified that the influence of environment noise, bias current and temperature drift on measured force can be reduced effectively, which improved the stability and accuracy of the measured static forces with noise of less than 0.9 mN. With cutting force measurement results compared with commercial dynamometer in cutting experiments, the proposed smart tool system had been validated to have a high sensitivity and high accuracy of in-process three axis cutting force measurement.

Application on the fabrication of more complex microsturctured and freeform surface, in-process feedback and controlling cutting status will be the future work.

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