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COUPLING CHARACTERISTIC ANALYSIS OF DYNAMOMETER BASED ON OCTAGONAL RING AND FBG SENSOR

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ABSTRACT

Milling force is an important parameter to describe the mechanical processing chip removal process, and it has a direct influence on generation of heat, tool wear or failure, quality of machined surface and accuracy of the work piece. Its accurate measurement is a significant basis for judging process state and improving the reliability of machining system. In this study, a dynamometer which uses octagonal ring as convert elastomer and FBG sensor as measuring element has been introduced. And the coupling characteristic which will affect the cutting force measurement accuracy of dynamometer among four elastic bodies located in dynamometer has been analyzed in theory. Besides, the simulation analysis of single octagonal ring and dynamometer which is used to verify the correctness of theoretical analysis has also been carried out, and the coupling characteristic of the real structure of dynamometer has been obtained. At last, the mathematical expression of the milling force component has been gotten by experiment, and it has also been amended by using the coupling characteristic of dynamometer.

KEY WOERDS

Octagonal ring; Dynamometer; Milling force; Coupling analysis

INTRODUCTION

Metal cutting is widely used in various industries, such as automotive, watercraft and project machine. During metal cutting, in order to prolong machine tool life and prevent tool breakage, mechanical properties of the milling tool should be known and therefore care should be taken to prevent this [1]. Cutting force is one of the most important mechanical properties in the machining process, and it can be used to judge the operation state of machine tool. Knowledge of cutting force is important in metal cutting, because it is used as a vital indicator in designing a machine tool, and also used for cutting process optimization [2], investigation of the fundamental study of cutting tools performance, prediction of surface roughness, tool wear monitoring [3], machining process planning [4-5] and others. Therefore, it is very significant to carry out cutting force measurement in the cutting process.

Cutting force dynamometers usually use sensitive elements to convert the cutting force into strain of sensitive elements, and the value of cutting force can be tested by measuring the strain. The sensors used in dynamometer are strain gage [6-10], piezoelectric element [11-14] or FBG sensor [15-18], etc. The strain type dynamometer is usually made up of four elastic elements; every two elements are located in the same direction to measure one horizontal component, and they are mutually vertical with the other two octagonal rings. In fact, when the external force was exerted, coupling, which would lead to the inaccurate measurement of the single direction force, would occur among the mutually vertical rings. Therefore, in order to improve the cutting force measurement accuracy, the coupling should be studied.

Compared with traditional sensors, FBG sensors are light in weight, small in volume, high in precision, immune to electromagnetic, resistant to corrosion and easy to conduct distributer dynamic measurement, so it is suitable for cutting force measurement. In this study, a dynamometer based on octagonal ring and FBG sensors has been introduced. And this paper analyses its cross coupling characteristics when it is utilized to measure the horizontal components, and gets the coupling characteristic of it. At the same time, the simulation analysis of single octagonal ring and dynamometer has been carried out. Then the coupling characteristic of the real structure of the measuring device has been obtained, and the correctness of theoretical analysis has also been verified. Finally, through the experiment, the mathematical expression of the milling force has been established; the correctness of the theoretical analysis and the simulation has also been certified. By using the coupling characteristic of dynamometer, mathematical expressions of milling forces have been amended, and then the decoupling of dynamometer can be realized.

1. MEASUREMENT PRINCIPLE OF DYNAMOMETER

1. 1 Measurement principle of octagonal ring

The design of octagonal ring is based on the deformation of ring. The deformation of ring under external loads is shown in Fig.1.

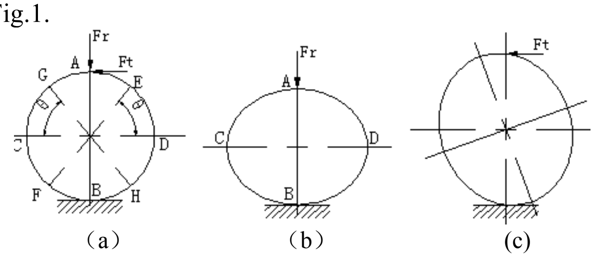

Figure 1. Deformation of ring under external loads

Under the action of vertical force Fr, the strain of points C and D is the largest except point A which is used for fixing ring, and the strain of points E, G, F and H is zero. Under the action of horizontal force Ft, the strain of points E, G, F and H is the largest, and the strain of points C and D is zero. By utilizing this characteristic of ring, FBG sensors can be pasted on points C and D to measure force Fr, similarly points G and E to measure force Ft. In order to facilitate the paste of sensors, octagonal ring which is easy to conduct the paste of sensors is utilized to replace ring in dynamometer, as shown in Fig.2.

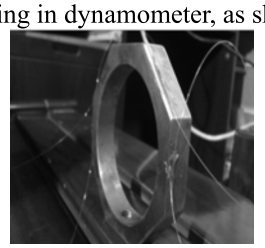

Figure 2. Octagonal ring

1.2 The structure of the measuring device

The basic structure of dynamometer which can measure three milling forces is shown in Fig. 3. From Fig. 3, we can see that milling force F_x is supported by A and C rings; milling force F_y is supported by B and D rings; milling force F_z that perpendicular to the working plane is supported by A, B, C and D rings.

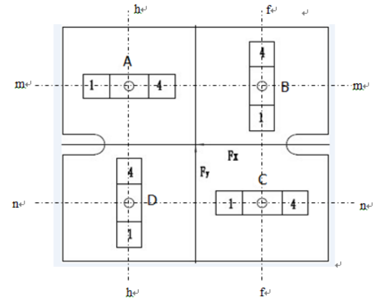

Figure 3. Structure of dynamometer

2. COUPLING ANALYSIS OF DYNAMOMETER

Given that the stiffness of A, B, C and D octagonal rings along the horizontal direction of the ring surface is K_{A1}, K_{B1}, K_{C1} and K_{D1} respectively, the stiffness in the direction that perpendicular to the ring surface is K_{A2}, K_{B2}, K_{C2} and K_{D2}, the stiffness along the radial direction is K_{A3}, K_{B3}, K_{C3} and K_{D3}. According to Fig.3, under the action of F_x, A and C rings are subject to the force along the horizontal direction of the ring surface and the force in the direction that perpendicular to the ring surface has been applied on B and D rings. Therefore, the simplified model of dynamometer can be established, as shown in Fig.4.

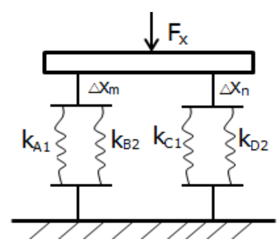

Figure 4. Simplified model of dynamometer acted by F_x

By using Hooke's law, F_x applied on dynamometer can be calculated out by using the following equation.

$$F_x = \left(K_{A1} + K_{B2}\right)\Delta x_m + \left(K_{C1} + K_{D2}\right)\Delta x_n \tag{1}$$

Where Δx_m is the elastic displacement in section m-m; Δx_n is the elastic displacement in section n-n.

Owing to the four octagonal rings is identical in size and physical parameters, the following equation can be obtained in theory.

$$\begin{gathered} K_{A1} = K_{B1} = K_{C1} = K_{D1} = K_1 \\ K_{A2} = K_{B2} = K_{C2} = K_{D2} = K_2 \\ K_{A3} = K_{B3} = K_{C3} = K_{D3} = K_3 \end{gathered} \tag{2}$$

By using the above equation, Eq.(1) can be rewritten as Eq.(3).

$$F_x = \left(\Delta x_m + \Delta x_n\right)K_1 + \left(\Delta x_m + \Delta x_n\right)K_2 \tag{3}$$

Under the action of F_y, the simplified model of dynamometer is shown in Fig.5. Then, the relationship between the deformation of ring and F_y is shown as follows.

$$F_y = \left(\Delta y_h + \Delta y_f\right)K_1 + \left(\Delta y_h + \Delta y_f\right)K_2 \qquad (4)$$

Where Δy_h is the elastic displacement in section h-h; Δy_f is the elastic displacement in section f-f.

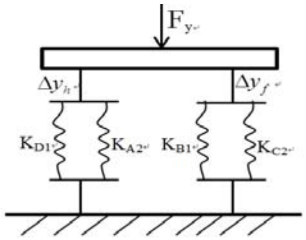

Figure 5. Simplified model of dynamometer acted by F_y

Under the action of perpendicular force F_z, the simplified model is shown in Fig.6.

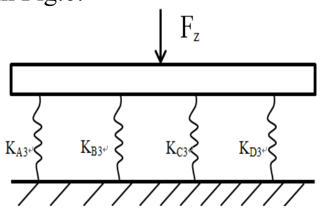

Figure 6. Simplified model of dynamometer acted by F_z

The relationship between the elastic displacement and F_z is shown in the follows:

$$F_y = K_3(\Delta Z_A + \Delta Z_B + \Delta Z_C + \Delta Z_D) \qquad (5)$$

Where Δz_A , Δz_B , Δz_C and Δz_D are the elastic displacement of A, B, C and D rings respectively when the dynamometer is acted by perpendicular force F_z.

In theory, only A and C rings are used to measure the horizontal component F_x, so the measured value of F_x is shown in the follows:

$$F_x = F_A + F_C = \left(\Delta x_m + \Delta x_n\right)K_1 \qquad (6)$$

In theory, only B and D rings are used to measure the horizontal component F_y, so the measured value of F_y is shown in the follows:

$$F_y = F_B + F_D = \left(\Delta y_h + \Delta y_f\right)K_2 \qquad (7)$$

Actually, B and D rings also bear certain load of F_x, and this leads the measured value of F_x measured by A and C rings is smaller than true value. It's the same for the measurement of F_y. Namely, there is cross coupling phenomenon when dynamometer is used to gauge the milling force F_x and F_y, and the proportional relation of milling force component between measured value and true value is $K_1/(K_1+K_2)$ which reflects the coupling degree of the octagonal rings. Under the action of F_z , all of the octagonal rings are used to measure it, so there is no coupling when dynamometer is utilized to measure vertical force.

3. SIMULATION ANALYSIS OF MEASURING SYSTEM

3.1 Simulation analysis of octagonal ring

In order to know the stain and the deformation of the octagonal ring when it is under the action of horizontal force, the simulation analysis of octagonal ring has been carried out. During the simulation analysis, the bottom of octagonal ring is fixed firstly， and a series of loads are exerted on point A to analyze its strain characteristic. Through simulation analysis, the strain values of each point under different loads can also be obtained, as shown in table.1.

Table1. Strain values of each point under the action of horizontal force

Force(N)	G($\mu\varepsilon$)	C($\mu\varepsilon$)	D($\mu\varepsilon$)	E($\mu\varepsilon$)
25	-8.3	-0.18	0.18	8.3
50	-16.5	-0.36	0.36	16.5
75	-24.7	-0.52	0.52	24.7
100	-32.9	-0.72	0.72	32.9
125	-41.17	-0.90	0.90	41.17

According to table.1, the strain of points C and D can be ignored, so taking the average strain value ε of points G and E, the relationship between the horizontal loads F and ε can be figured out.

$$\varepsilon = 0.3293F \qquad (8)$$

The load values and the corresponding deformations can also be obtained, and then the stiffness in different directions can be calculated. Under the action of 100N, the deformation nephograms of octagonal ring in horizontal and lateral direction are shown in Fig.7 and Fig.8 respectively.

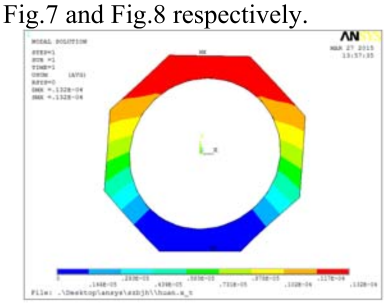

Figure 7. Deformation nephogram of octagonal ring under the action of 100N

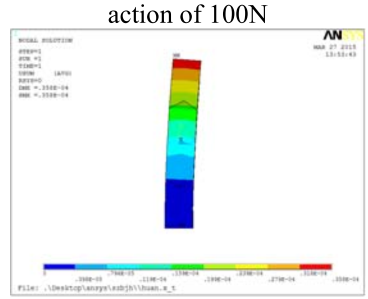

Figure 8. Deformation nephogram of octagonal ring under the action of 100N

The deformation value of octagonal ring in each direction can also be calculated out, and then the stiffness can be obtained by using mechanical materials. The stiffness in horizontal direction is $7.57\times10^6 N/m$, and the stiffness in lateral direction is $2.79\times10^6 N/m$.

3.2 Simulation analysis of dynamometer

After the simulation analysis of octagonal ring, the simulation analysis of the dynamometer under different loads has also been carried out. Firstly, the lower platform of dynamometer has been fixed, and then the loads up are 125N×25N intervals has been applied on the middle of the upper platform. When the dynamometer is under the action of horizontal loads F_X, the strain values of each point of A and C rings can be obtained. And the measured value F_x can be calculated by Eq.(6) and Eq.(8), as shown in table.2.

Table2. The force F_x measured by A and C ring

F_X (N)	25	50	75	100	125
F_x (N)	18.13	36.27	54.39	72.53	90.66

According to table.2, the relationship between true value F_X and measured value F_x is shown as follows.

$$F_x = 0.7253 F_X \tag{9}$$

Similarly, the relationship between true value F_Y and measured value F_y is shown as follows.

$$F_y = 0.7253 F_Y \tag{10}$$

Bring the stiffness value of the octagonal ring to the equation K1/ (K1+K2), the proportional relation of milling force component between measured value and true value in theory is as follows.

$$\frac{K_1}{K_1+K_2} = \frac{7.57}{7.57+2.79} = 0.7307 \tag{11}$$

It can be seen from Eq.(9), Eq.(10) and Eq.(11) that the coefficients calculated by two ways are very close, and it also proves the correctness of the coupling analysis in theory, namely the coupling degree of octagonal rings is related to the stiffness of the rings.

4. EXPERIMENTAL STUDY ON COUPLING CHARACTERISTICS OF DYNAMOMETER

In order to build function model between force and the change of reflected wavelength of FBG sensors, the four octagonal rings have been calibrated respectively. In the test, the horizontal force along the direction of the cross section of octagonal ring has been applied on each octagonal ring, and the loads up are 125N×25N intervals. After each load, the change of reflected wavelength of FBG sensors pasted on octagonal ring has been recorded. Taking the average value of wavelength change of measuring point G and E, the function models of four octagonal rings can be obtained as shown in Fig. 9.

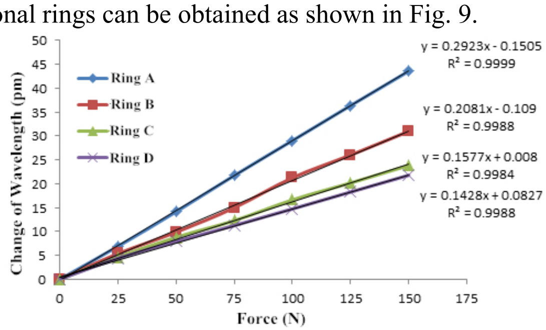

Figure 9. Calibration experiment of octagonal ring

According to Fig.9, the strain character of four rings in horizontal direction is different from each other, and the sensibility is lower than the simulation analysis. That is because error existed in the process of actually manufacture and installation of each octagonal ring, and the strain transfer efficiency of FBG sensors are not exactly the same.

4.2 Experiment of the octagonal ring's stiffness characteristic

For the sake of getting the real stiffness of octagonal ring, several tests have been finished. In each trial, the loads up to 125N×25N intervals have been applied on octagonal ring, and after each load, the displacement of its top in X direction has been measured by laser displacement sensor. Take the octagonal ring C as an example, under different loads, the stiffness of it along X direction is shown in table.3.

Table 3: Measured displacement and stiffness of C ring under horizontal load

	25N	50N	75N	100N	125 N
Displacement(μm)	11.7	22.5	35.2	47.2	59.8
Stiffness (10^6N/m)	2.14	2.22	2.13	2.12	2.16

As is shown above, the difference of stiffness value calculated under different load is small, the average stiffness value of ring C along the X direction is 2.15 × 10^6N/m. Therefore, the stiffness value along different direction of four rings can be obtained, as shown in table.4.

Table 4. The stiffness of all rings in different directions

	A	B	C	D
Horizon(10^6N/m)	2.15	2.85	2.15	2.81
Side(10^6N/m)	1.23	1.13	1.20	1.26

According to table 3, we can take $2.15\times10^6\,N/m$ as K_1 and the average value of the side stiffness of B and D rings as K_2. The measured coupling degree of milling force F_x is shown as follows.

$$\frac{2.15}{2.15+1.19}=0.6428 \tag{12}$$

4.3 Experiment on the coupling characteristics of the measuring device

Cross coupling will occur when dynamometer is used to measure F_x and F_y. Take measuring the milling force F_x as an example, the measured value equals the sum of forces imposed on ring A and ring C.

$$F_x = F_A + F_C = \frac{\Delta\lambda_A + 0.1505}{0.2923} + \frac{\Delta\lambda_C - 0.008}{0.1577} \tag{13}$$

Where $\Delta\lambda_A$ is the change of reflected wavelength of FBG sensors pasted on point A of the octagonal ring; $\Delta\lambda_B$ is the change of reflected wavelength of FBG sensors pasted on point B of the octagonal ring.

In order to know the difference between measured value and true value, the loads up to 150N×25N intervals along X direction have been applied on dynamometer. Then the value of FBG sensor pasted on points G and E of A and C rings can be obtained, as shown in table.5.

Table 5. Wavelength change of FBG sensors pasted on points G and E of A and C rings

Force(N)	A-G(pm)	A-E(pm)	C-G(pm)	C-E(pm)
25	3.01	2.02	1.21	1.05
50	6.27	4.18	2.45	2.14
75	9.06	6.40	3.59	3.25
100	12.76	8.51	4.72	4.31
125	16.23	10.82	6.91	5.34
150	19.26	13.14	8.21	6.41

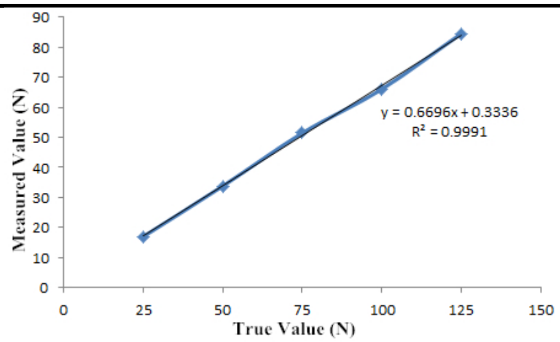

Figure 10. Fitted curve of measured value and true value of component force in x direction

Under different loads, the corresponding measured value F_x can be calculated out by using the Eq.(13) and the data in table 5. Then, we can get the fitting curve between measured value and true value of the milling force in X direction, as shown in Fig. 10.

According to the above, the coupling degree in X direction calculated by the above two ways is quite close, and the difference is less than 4% which can proves that the coupling degree of dynamometer is related to the stiffness of octagonal rings in the same direction. At the same time, the larger the stiffness of ring A and ring C along the direction is, the smaller the degree of coupling that ring B and ring D act on A and C rings is, and the coupling degree will be more smaller.

The measured value of component force in X direction can be modified, and the modified mathematical expression is as follows.

$$F_x = \frac{1}{0.6696}\left(\frac{\Delta\lambda_A + 0.1505}{0.2923} + \frac{\Delta\lambda_C - 0.008}{0.1577}\right) \tag{14}$$

Where $\Delta\lambda_C$ is the change of reflected wavelength of FBG sensors pasted on point C of octagonal ring.

Similarly we can get the modified expression of the milling force in y direction.

$$F_y = \frac{1}{0.7053}\left(\frac{\Delta\lambda_B + 0.109}{0.2081} + \frac{\Delta\lambda_D - 0.0827}{0.1488}\right) \tag{15}$$

Where $\Delta\lambda_D$ is the change of reflected wavelength of FBG sensors pasted on point D of octagonal ring.

5. CONCLUSIONS

In this study, the coupling characteristic of dynamometer has been analyzed in theory. The conclusion that the coupling degree is related to the stiffness of the octagonal ring has been obtained. The simulation analysis of single octagonal ring and dynamometer has also been done, and it confirms the correctness of theoretical conclusion. In order to get the real coupling degree and certify the theoretical analysis and simulation analysis, the calibration experiment on four octagonal rings and the coupling characteristic experiment on dynamometer have been carried out. The function between measured value and true value of horizontal force has been established, moreover, the computational formula of horizontal force which can solve the coupling existed in dynamometer and improve the cutting force measurement accuracy has been amended by using the cross coupling characteristic of dynamometer.

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