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ORIGINAL ARTICLE

A novel dynamometer for monitoring milling process

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Abstract Cutting force measurement is an essential requirement in tool condition monitoring and offer an important indicator to design machine tools, optimize machining processes. In this paper, a novel cutting force dynamometer for measuring axial force and torque in milling is proposed. The new type sensing element has been developed to enhance the sensitivity of the dynamometer meanwhile to maintain enough rigidity. The device is based on semiconductor strain gauge that measures the deformation of lantern-shape sensing element. In order to check the feasibility of the proposed dynamometer, a static calibration and modal impact test were carried out, and the performance of device installed on a milling machine has been tested under different cutting conditions. The results show that the dynamometer has a high performance and could be used as an instrument for monitoring machining process.

Keywords Dynamometer · Cutting force · Sensitivity · Strain gauge

1 Introduction

Cutting force is one of the critical indicators in manufacturing processes. The unordered variation of cutting force may cause abnormal tool wear, tool breakage and poor surface roughness, which reduce dimensional accuracy and product quality. More seriously, it may threaten the safety of the operator. An automatic system for cutting force detection is an alternative solution to this problem. The development of cutting force dynamometer has contribution to high machining precision, intelligent manufacturing, and optimization of manufacturing process. Therefore, various direct and indirect cutting force monitoring systems have been proposed and developed in the last 20 years. Cutting force measurement is based on some typical sensing techniques, which include piezoresistive sensors, piezoelectric sensors, capacitive transducers, and resonant sensors.

Some interesting examples of measurement for cutting forces monitoring in milling process can be found in literatures. For instance, YaldIz S et al. [1] developed a four-component platform dynamometers based on strain gauge, which can measure tri-axial and torsional forces, but it is limited by the drawbacks of low stiffness and low frequency bandwidth. On the other hand, because of a better balance of high rigidity and sensitivity, piezoelectric effect-based table dynamometers are more commonly used in laboratories for fundamental research at present. However, the table dynamometer must be clamped between the machine table and workpiece when measuring cutting force, which undoubtedly limits the geometry and dimension of the workpiece. Due to complicated installation and high cost, the table dynamometer is not the best choice as an instrument used in industry. Thus, to overcome these drawbacks, it is necessary to develop a flexible rotating dynamometer that is integrated to the spindle. C. Scheer et al. [2] and S. S. Park et al. [3], Byrne and O'Donnell [4] proposed spindle-integrated force ring sensor based on piezoelectric effect used in milling and drilling processes. A 3D piezoelectric rotating dynamometer which clamped in the tool holder has been developed for measuring tri-axial cutting force in face milling by Totis et al. [5]. Alternatively, capacitive sensor and strain gauge sensor can

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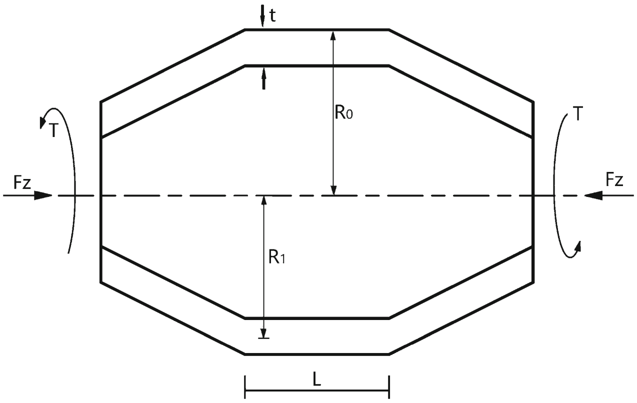


Fig. 1 Structure of simple lantern model

measure the cutting force by the elastic deformation of the sensing element. Albrecht et al. [6] integrated the capacitive sensors into spindle to indirectly measure radial force in milling process. Rizal [7], Suprock [8], and Nichols [9] designed and developed strain gauge-based integrated dynamometer to measure cutting force in their studies. As an adapting piece between spindle and cutting tool, various structures of sensing elements were developed by researchers, such as thin-walled cylindrical [10, 11], symmetrical cross beam [7, 12], octagonal ring [1, 13], modification of two slotted disks [14], and modified standard CNC tool holder [15]. Some indirect cutting force measurement systems were also proposed by researchers. For example, Kim JH et al. [16] developed a cylindrical capacitive displacement sensor which could effectively remove surface roughness of the target area. The sensor was suitable in the monitoring of high-speed cutting conditions. P. Albertelli et al. [17] proposed a novel methodology for the in-process indirect estimation of cutting forces and tool tip vibrations (displacement and bending deflection) in milling operations. H. C. Möhring et al. [18] proposed the combined application of the sensory

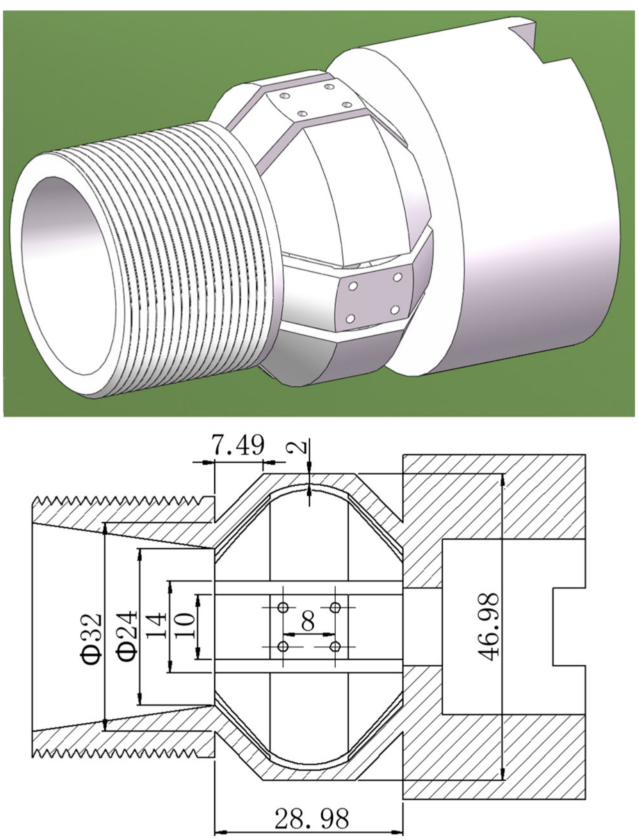


Fig. 2 Structure and dimensions of dynamometer

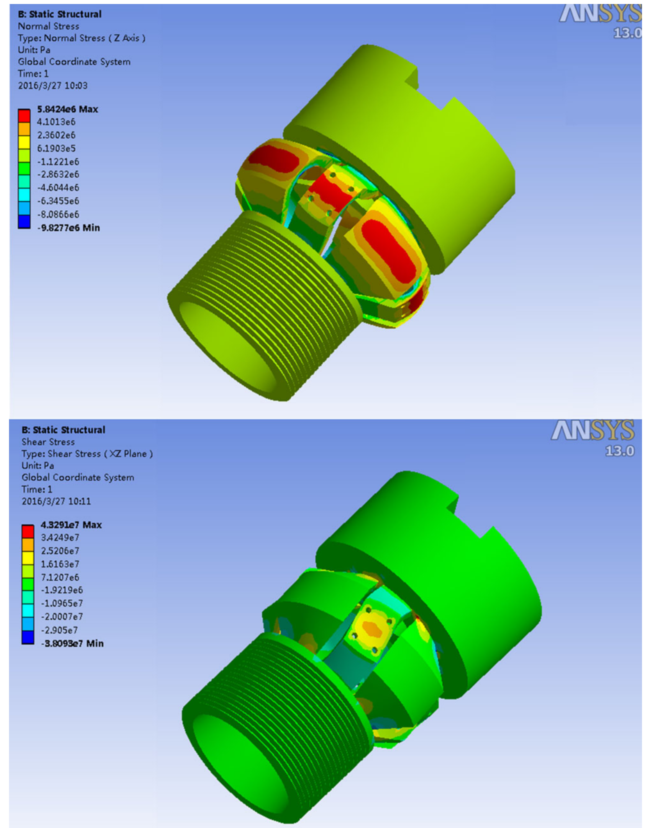


Fig. 3 Finite element simulation under axial force and torque

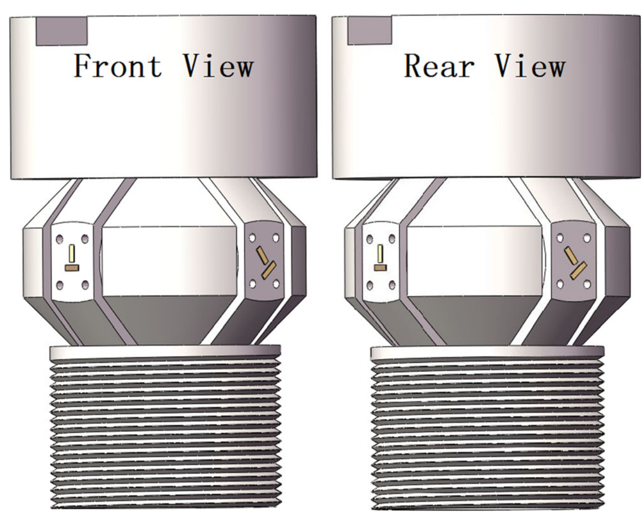


Fig. 4 Arrangement of strain gauges for measuring

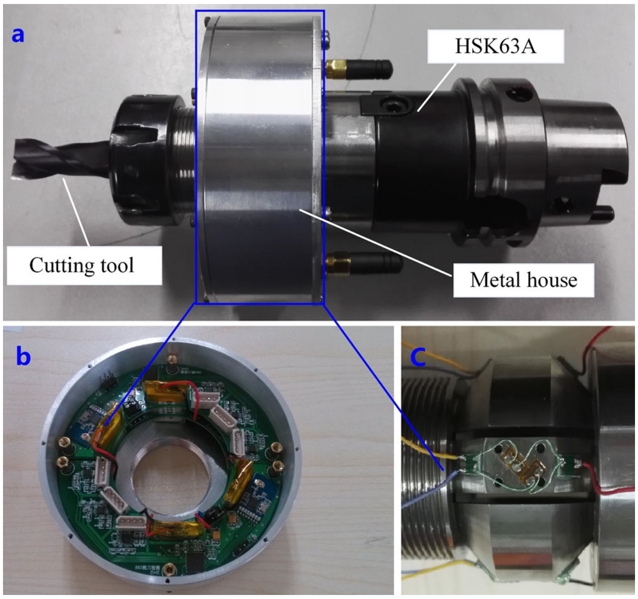


Fig. 5 Prototype of the new measuring device

fixture and the adaptronic spindle for process monitoring for the first time. B. Denkena et al. [19] described that how the exciting force at a certain location of a compliant mechanical structure can be determined by consideration of the system's dynamics in combination with stochastic estimation (Kalman Filter). Ma Lei et al. [20] developed a novel, low-cost thin-film PVCD sensor, and proposed a nonintrusive method of monitoring the feed and transverse forces in the peripheral end milling process.

Optimization of design parameter requires not only optimal natural frequency and sensitivity but also low cross-interference. A more flexible and cost-effective dynamometer is desirable in industry. Thus, in order to provide a basis for the intelligent milling systems, this study developed a novel structure dynamometer based on semiconductor strain gauge which is installed on a tool holder of HSK (Hohl Shaft Kege) and is capable of measuring axial force and torque. The performance of the dynamometer is confirmed through static and dynamic evaluation tests. Results of the tests showed the new structure has high sensitivity, high natural frequency, and low cross-interference in addition to low cost. And the cutting tests showed the dynamometer could detect the dynamic cutting force stably.

2 Principle and fabrication

The purpose of this study is to develop a high-performance dynamometer capable of measuring axial force and torque during high-speed milling process. A novel structure of lantern was put forward for measuring axial force and torque as depicted in Fig. 1. The lantern shape is selected as simplified model of the designed sensor due to the inspiration of cylindrical theory as below:

$$\sigma_{\max} = \frac{y_A E}{R_0} \tag{1}$$

$$y_A = \frac{F_Z R_0}{2D\lambda^2} \cdot \frac{C_1}{C_2} \tag{2}$$

$$D = \frac{Et^3}{12(1-\nu^2)} \tag{3}$$

$$\lambda = \left[\frac{3(1-\nu^2)}{{R_0}^2 t^2}\right] \tag{4}$$

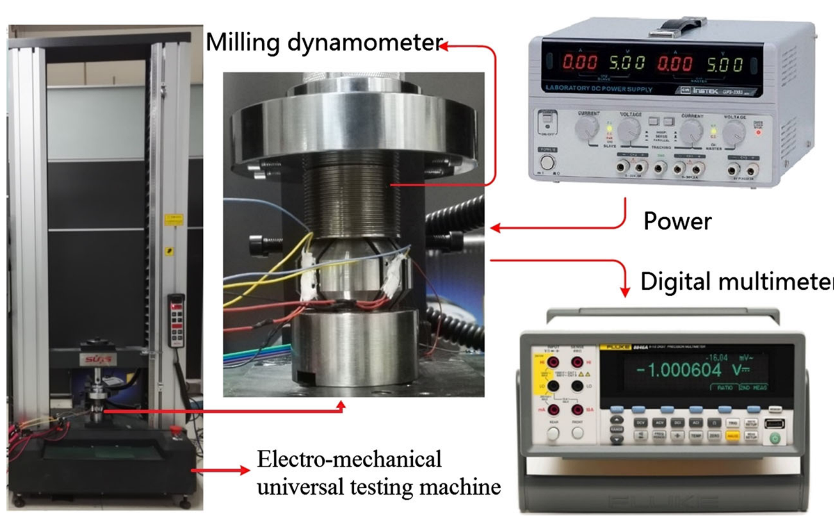
$$C_1 = \sinh^2 \lambda l + \sin^2 \lambda l \tag{5}$$

$$C_2 = \sinh^2 \lambda l - \sin^2 \lambda l \tag{6}$$

$$\tau = \frac{T}{2\pi {R_1}^2 t} \tag{7}$$

As illustrated in Fig. 1, when axial force (F_Z) is applied to the lantern shape, the outer surface stress caused by F_Z can be

Fig. 6 Experimental setup for axial force static calibration



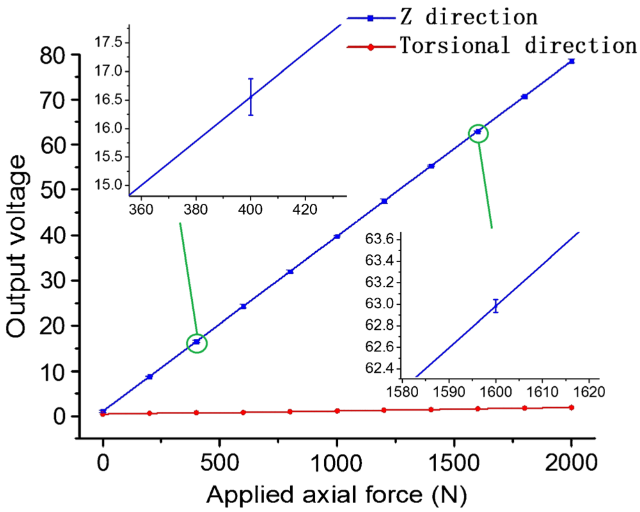


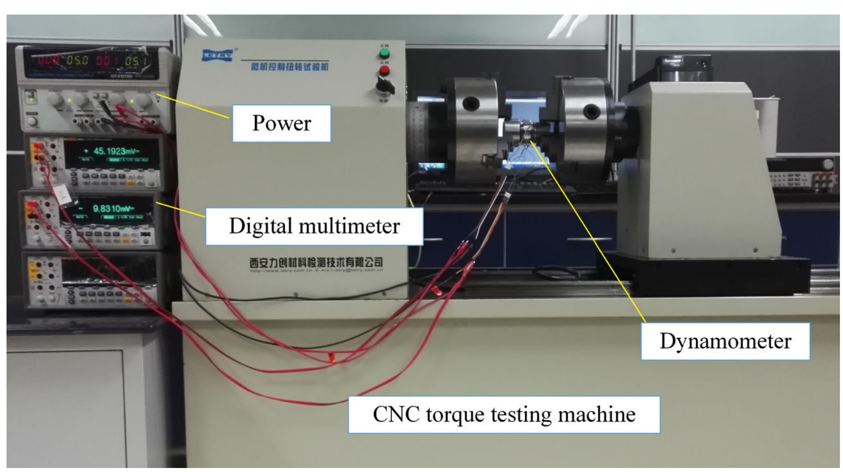
Fig. 7 The calibration results applied axial force

calculated by Eqs. (1)–(6); when torque (T) is applied to the lantern shape, the outer surface shear stress caused by T can be calculated by Eq. (7). Where, σ denotes the surface stress of lantern shape; τ denotes the surface shear stress of lantern shape; y_A, D, λ, C_1, and C_2 are constants about lantern-shape parameters (i.e., R_0, R_1, t, and l); R_0, R_1, t, L, E and υ represent lantern's external radius, mean radius, thickness of middle section, length of middle, elasticity modulus, and Poisson's ratio of material; equations above indicate that lantern shape's surface stress is proportional to axial force and torque.

In designing the multicomponent force dynamometer, it is often desirable to have the least cross-interference error when all forces are applied simultaneously. Furthermore, the sensitivity for the dynamometer should be high as much as possible. Hence, a novel sensing element that has a sectional shape of optimized lantern is proposed for measuring the cutting force in both axial and torsional direction. The improved lantern structure and major dimensional characteristics of the novel dynamometer are reported in Fig. 2. The proposed sensing structure involved three distinct sections, and the middle section of them contained four critical places to install strain gauges. As it is difficult to obtain theory formula to calculate the surface stress of the optimized lantern shape, a conventional finite element software (ANSYS) was used to simulate and analyze the proposed sensing structure. Element type Solid 92 was selected for finite element method (FEM) analysis. The AISI630 (PH17–4) stainless steel was chosen in this investigation due to its excellent elastic properties. Therefore, modulus of elasticity and Poisson's ratio for the mentioned material were respectively considered as 197 and 0.272 GPa throughout the FEM analysis. The results of FEM analysis are illustrated in Fig. 3, which indicates that the locations of the stress concentration were situate on the middle platform of the outer surface when applied axial force or torque. These locations were applied to mount strain gauges so as to have a higher sensitivity for dynamic measurement. Strains (proportional to the mechanical stresses) will be accumulated on the strain gauges when the sensing element is subjected to small mechanical deformation. The strain can then be converted into a voltage signal by Wheatstone bridge circuit.

During the milling process, the cutting tool is subjected to various loadings. For example, the torque imposed on the dynamometer may cause shear deformation on the cylindrical shell, and axial cutting forces can produce axial tensile or compressive strains. In order to measure the milling torque, it is critical that the strain gauges only pick up the shear strain and ignores all other disturbances. In this regard, measuring axial force also needs to only pick up the axial strain. A schematic of strain gauges arrangement is shown in Fig. 4, which is designed to fulfill the mentioned requirement. It consists of two couples of Wheatstone bridge circuits including eight individual semiconductor strain gauges whose silicon size is 3.8 mm × 0.22 mm × 0.05 mm each one, and the resistance is around 1 kΩ.

Fig. 8 Experimental setup for torque static calibration



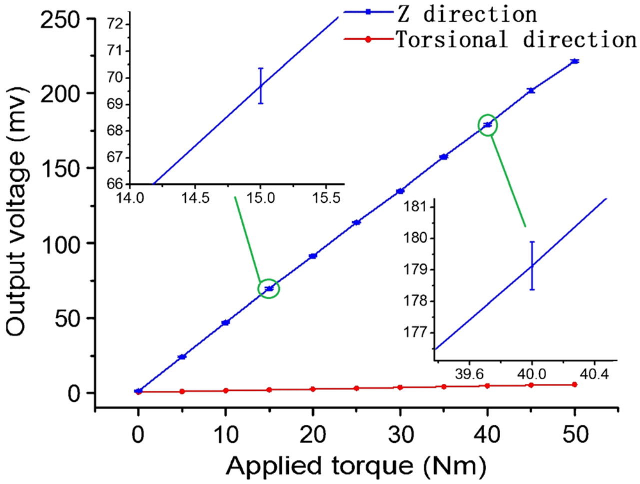


Fig. 9 The calibration results under torque

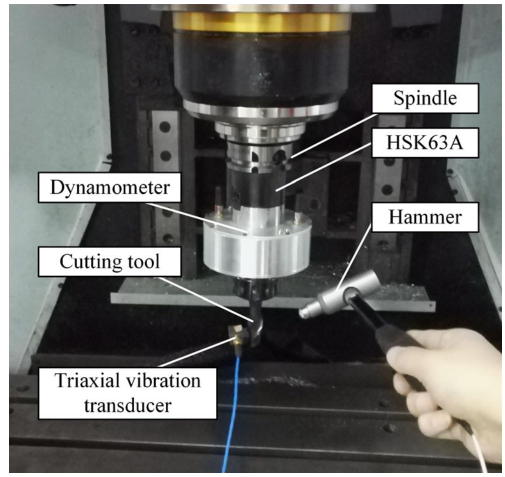


Fig. 11 Experimental setup of the modal impact tests

The two strain gauges in one couple are aligned at 45° with respect to the central axis of the spindle, which are exactly symmetrical to the remnant strain gauges in the same couple attached on the opposite surface of the circle. The other couple was mounted in the same way except that they are aligned at 0° and 90° along the central axis. Due to symmetry of the host structure and sensor arrangement, the cross-interference of axial tensile or compressive strains and shear strain will be minimized. A prototype of the dynamometer system was fabricated and is shown in Fig. 5. The cutting force was measured by means of the developed dynamometer, which mounted on a standard HSK-63A toolholder as shown in Fig. 5a. Part strain gauges are attached to the surface of the lantern shape as shown in Fig. 5c. These strain gauges are low in cost and are easy to be firmly fixed to the surface of the sensing element. All the electronics and batteries are located in a metal housing that is mechanically attached to the dynamometer as illustrated in Fig. 5b.

3 Preliminary tests

3.1 Static calibration

As shown in Fig. 6, the testing apparatuses used to measure the axial force are constitutive of an electro-mechanical universal testing machine (type UTM6104, SUNS Technology, Shenzhen, China) which could provide constant force, two digital multimeters (8846A, FLUKE CORPORATION, Everett, WA, USA) which could record output voltage, and a power supply (GPS-3303C, GWINSTEK Electronic Technology Co. Ltd., Suzhou, China) which could apply a voltage of 5 V DC. During the test, axial forces were applied to the dynamometer end face by the electronic force regulator. The force was applied from 0 to 2000 N with an interval of 200 N, and each interval would be maintained for 30 s. Five cycles including loading and unloading procedures were implemented. Figure 7 depicts the calibration results under axial force. As shown in Fig. 7, sensitivity, cross-sensitivity errors, linearity, repeatability, and hysteresis of the dynamometer

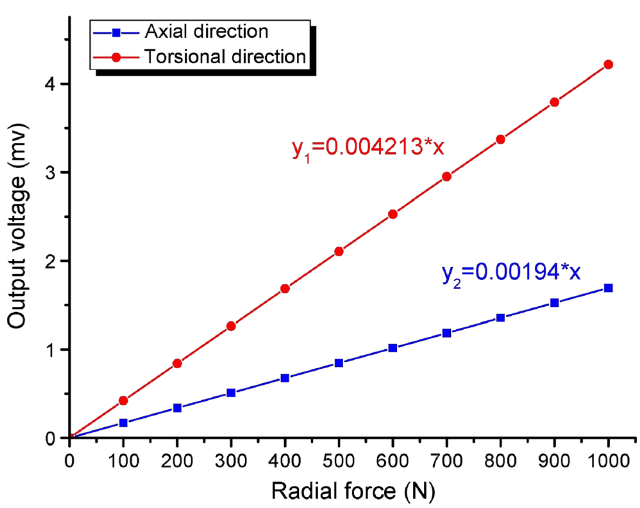


Fig. 10 The calibration results under radial force

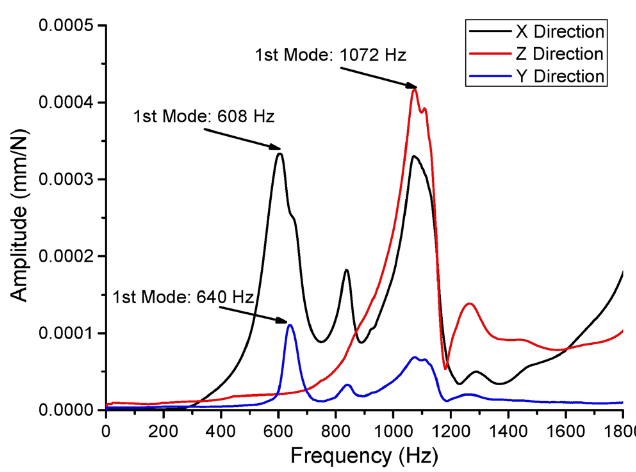


Fig. 12 Frequency response function of the cutting tool/tool holder/spindle/machine tool system used in the study

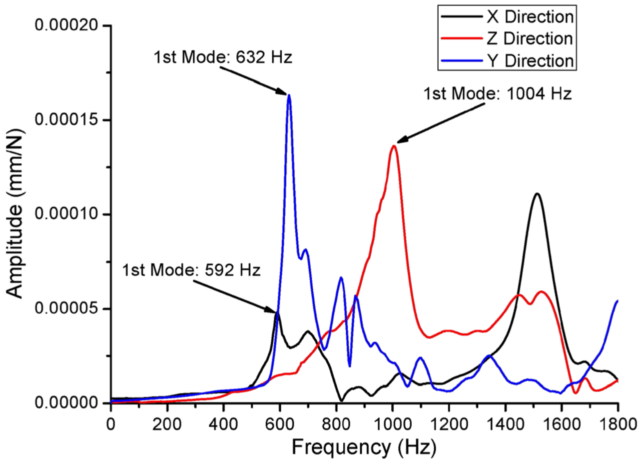


Fig. 13 Frequency response function of the cutting tool/tool holder/dynamometer/spindle/machine tool system used in the study

under axial force are 3.87 × 10^{-2} mV/N, 1.90, 0.20, 1.29, and 0.40%, respectively.

On the other hand, the testing apparatuses used to measure the torque are shown in Fig. 8, which include a CNC torque testing machine (WNZ-200, XI'AN LETRY, Xi'an, China) that could provide constant torque force, two digital multimeters, and a power supply same as used in axial force calibration test. The measurement range of the torque force is expected to be 0–50 Nm. The applied torque forces were raised from zero to its maximum value in steps of 5 Nm and maintained for 30 s each time. Five cycles including loading and unloading procedures were implemented. The main static performance characteristics of the dynamometer under torque force are shown in Fig. 9. It indicates that sensitivity, cross-sensitivity errors, linearity, repeatability, and hysteresis of the sensor are 4.40 mV/Nm, 2.36, 0.56, 1.04, and 0.57%, respectively.

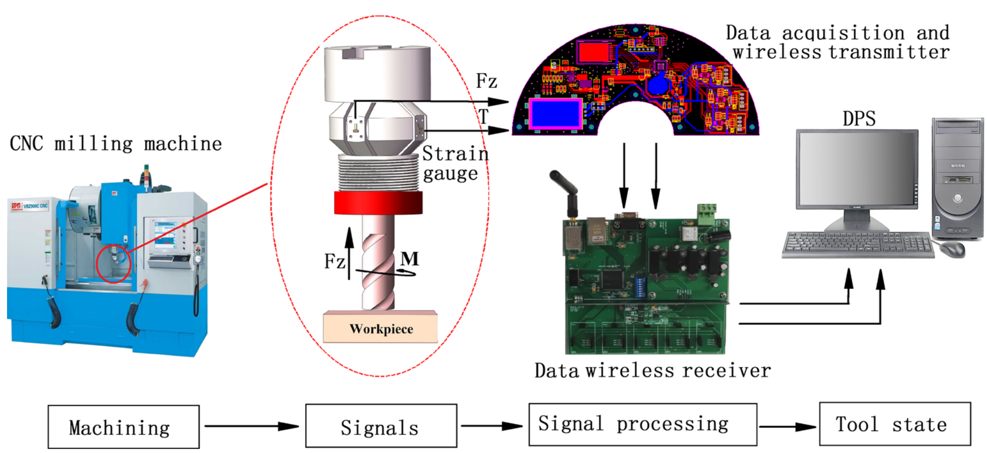
In practice, radial force would be generated when the cutting tool cuts the workpiece material. The effect of radial force on the axial force and torque measurement cannot be ignored. For the purpose of verifying cross-effects on axial stress and shear stress, the static calibration of axial direction and torsional direction sensitivities under radial force performance were performed. Five cycles including loading and unloading procedures were implemented. As shown in Fig. 10, the sensitivities are 1.94 × 10^{-3} and 4.21 × 10^{-3} mV/N in axial and torsional directions. To compare with Figs. 7 and 9, it can be seen that the effect of sensitivity under radial force for measuring axial force and torque does not exceed 5.01 and 0.1%. To be exact, the effect of radial force on the axial force and torque measurement are not very obvious.

3.2 Dynamic property

The stiffness is a critical parameter of the dynamometer to reflect its dynamic property. In other words, the natural frequency should be high enough to ensure that collected signals would not be disturbed during the machining process. A stationary impact hammer test was performed to find the lowest natural frequency of the system used in this study in the feed X, Y, and Z directions. As shown in Fig. 11, the dynamometer was excited by a modal impact hammer (type 086D05) when it was installed on the machining system, and a tri-axial vibration transducer (type 95663) was connected to the sensing element. The signals excited by hammer and vibration transducer were acquired by a data acquisition and modal analysis system (type SCADAS305) manufactured by LMS Company (Leuven, Belgium).

The stiffness of system would be reduced after the mounted dynamometer, because extended length of cutting tool was increased, so the impact tests of cutting tool/tool holder/spindle/machine tool system and cutting tool/tool holder/dynamometer/spindle/machine tool system were carried out to find the changing of frequency response function; each impact test was repeated 10 times for each direction. The displacement form of the FRFs is shown in Figs. 12 and 13. It can be seen that the first stationary modes of the X, Y, and Z directions are nearby 608, 640, and 1072 Hz without mounting the dynamometer, respectively. The first stationary modes of the X, Y, and Z directions reduced to 592, 632, and 1004 Hz when the

Fig. 14 Cutting test setups



dynamometer was mounted on the tool holder. Because FRF in torsional direction can be assumed to have higher stiffness than their stationary counterparts, the first mode in the torsional direction is expected to be higher than 1004 Hz. So it can be considered that the system is applicable as long as the excitation frequency of the cutting force is below 592 Hz. In any case, their values can be considered acceptable for typical frequency range of milling operation. These results show that the properties of the dynamometer guarantee that no resonance situation should occur during machining process.

4 Cutting tests and results

To verify the proposed force measurement system, the machining tests were performed on a CNC milling machine (manufactured by HNC, Wuhan, China) under dry cutting condition. The details of the machining experimental setups are shown in Fig. 14. During the milling operation, axial force and torque could be regarded as the measured indicators to represent the machining state. The cutting force measurement based on a low-cost data acquisition system was developed and used to monitor the cutting process. The data monitoring system is comprised of a data acquisition and transmitter module, a data receiver and a processing software on computer, which could acquire signals at a sampling rate of 10 KHz and wirelessly transmitted to a nearby base station in real time.

Dynamic cutting tests were performed in order to evaluate the performance of the developed dynamometer in real operation. The cutting tests were operated under dry cutting condition as shown in Fig. 15. The workpiece materials used were Aluminum 7075 (AL7075) and ASTM 1045. The cutting tool was a three-toothed end mill with a diameter of 16 mm, and the helix angle was 45°. No cutting fluid was used in the tests. All other cutting conditions used in the experiments are listed in Table 1. In addition to the lantern-shape dynamometer, a

Table 1 Milling parameters and maximum force values measured in axial and torsional directions

No.	Spindle speed (rpm)	Axial depth of cut a_p (mm)	Radial width of cut a_e (mm)	Feed per tooth a_f (mm)	Workpiece material	Axial force F_z (N)	Torque T (Nm)
1	500	1	16	0.067	AL7075	75.56	2.68
2	500	1	5.3	0.067	AL7075	69.25	2.62
3	500	1.5	16	0.067	AL7075	112.35	3.86
4	500	1.5	5.3	0.067	AL7075	102.94	3.78
5	1000	1	16	0.067	AL7075	85.71	2.72
6	1000	1	5.3	0.067	AL7075	78.39	2.57
7	1000	1.5	16	0.067	AL7075	128.18	3.83
8	1000	1.5	5.3	0.067	AL7075	117.59	3.67
9	1500	1	16	0.067	AL7075	74.48	2.61
10	1500	1	5.3	0.067	AL7075	67.74	2.57
11	1500	1.5	16	0.067	AL7075	108.72	3.77
12	1500	1.5	5.3	0.067	AL7075	102.61	3.63
13	2000	1	16	0.067	AL7075	71.67	2.58
14	2000	1	5.3	0.067	AL7075	65.98	2.52
15	2000	1.5	16	0.067	AL7075	105.95	3.67
16	2000	1.5	5.3	0.067	AL7075	98.32	3.64
17	1200	1	1.5	0.100	ASTM 1045	71.23	3.75
18	1200	1	1.5	0.115	ASTM 1045	82.16	4.12
19	1200	0.8	0.5	0.100	ASTM 1045	53.34	1.35
20	1200	1.6	0.5	0.100	ASTM 1045	65.39	2.76
21	1200	2.4	0.5	0.100	ASTM 1045	80.61	4.11
22	1200	3.2	0.5	0.100	ASTM 1045	92.52	5.54
23	1200	4	0.5	0.100	ASTM 1045	105.27	7.01

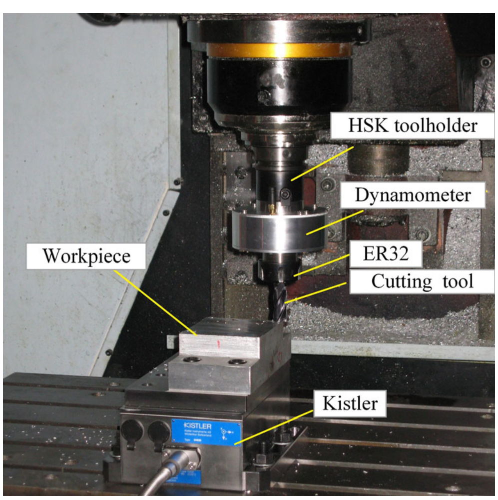


Fig. 15 Dynamic cutting experiment

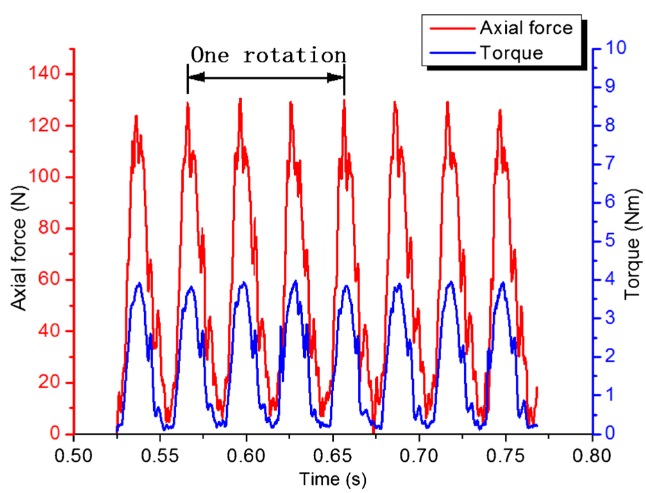


Fig. 16 Cutting force signals at a cutting speed of 1000 rpm

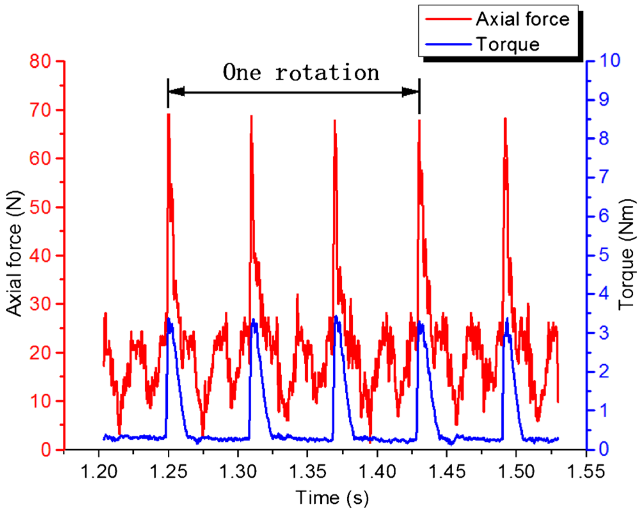


Fig. 17 Cutting force signals at a cutting speed of 500 rpm

three-component piezoelectric platform dynamometer (Kistler 9257B) was used to measure cutting force components produced in a peripheral end milling experiments. By using a combinational method, 23 combinations of experimental were performed as shown in Table 1. The table also lists the results of axial force and torque that obtained from the cutting tests.

Figure 16 shows the results of measured milling torque and axial forces with a spindle speed of 1000 rpm, axial depth of 1.5 mm, and radial width of 16 mm, where the measured frequency generated by the milling tool tooth is 50 Hz. When the spindle speed is changed to 500 rpm, axial depth and radial width are separately 1 and 5.3 mm; the test results can be seen in Fig. 17. By analyzing the obtained signals, it can be evaluated that the influences of cutting parameters, instantaneous torque, and axial force are visible in these signals. Figure 18 shows the comparison between the axial force measurements performed with the developed dynamometer and commercial devices (Kistler 9257B). The Kistler dynamometer was also sampled at 10 kHz with a National

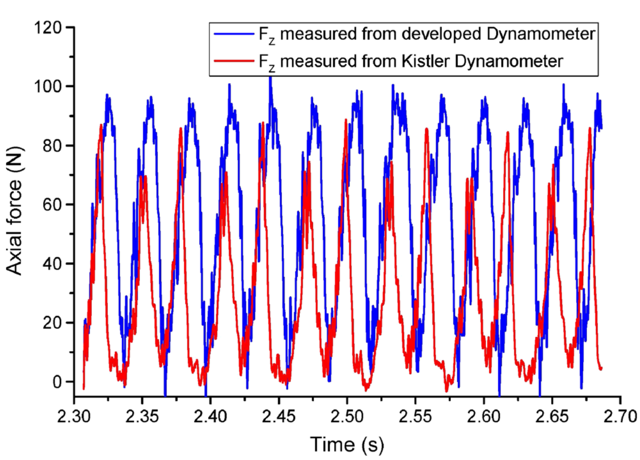


Fig. 18 Comparison of F_Z between the reference signal measured from Kistler and the in situ measured lantern-shape dynamometer signal

Table 2 Roughness on surface of Al workpiece after milling

Spindle speed(rpm)	Before installing dynamometer (μm)	After installing dynamometer (μm)
500	1.131	1.166
1000	1.080	1.104
1500	1.056	1.087
2000	1.044	1.079

Instrument data acquisition system. Compared to cutting force signals measured from Kistler 9257B, it can be seen that the spectrum of the developed dynamometer signal is similar to that of the Kistler dynamometer force signal, especially at the tooth passing frequencies. This similarity is expected, because during the periodic of cutting the workpiece, the forced vibration at the spindle speed-related frequencies will directly impact both dynamometers. However, it is also observed that the developed dynamometer capture the periodic force vibration at spindle frequencies and tooth passing frequencies.

In order to verify the influence to surfaces quality when the developed dynamometer mounted on the tool holder, roughness tester was used for measuring the roughness on the surface of Aluminum 7075 workpiece after milling process. As shown in Table 2, it can be seen that the roughness on workpiece surface have a slight change after installing the dynamometer compared with before installing the dynamometer on the tool holder. In other words, the dynamometer has no obvious disadvantage to the surfaces quality.

5 Conclusion

In this work, a novel strain gauge-based rotating dynamometer for monitoring milling process was developed. The dynamometer is capable of measuring the torque and axial force. It could be compatible to several types of cutting tools and has no constraints on the machining condition such as tool dimensions and workpiece dimensions. The calibration results show that sensitivity of axial force and torque approximately are 3.87×10^{-2} and 4.40 mV/Nm, and cross-sensitivity errors are below 1.90 and 2.36%. In a sense, the radial force could be ignored, since it merely has a slight effect in the output of axial force and torque measuring. The results of modal impact tests show that the lowest natural frequency of the force measurement system in all force orientations is 592 Hz when the dynamometer is mounted on the spindle. This means that with a high sensitivity, its dynamic performance is still suitable for applying in machining process. The cutting tests indicated that the cutting forces are clearly visible in the signals. The dynamometer has no significant influences to the stiffness of the measurement system and the surfaces quality. Predictably, the developed dynamometer could be used to monitor cutting process including chatter detection, tool wear monitoring, and tool breakage detection and optimize parameter design of machine tool. It is worth to note that the tool holder was not balanced after installing the developed dynamometer. For industrial applications, the metal housing and signal processing circuit needs to be designed such that it does not add to rotational imbalance of the tool holder. Future work will include improving the accuracy of force measurement system and reducing the imbalance caused by dynamometer.

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