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The Design of Force Measuring Tool Holder System Based on Wireless Transmission

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ABSTRACT Cutting force can be used in monitoring machine processes and for guiding production. Therefore, the measurement of cutting forces has significant meaning in research. In this paper, an innovative force measuring tool holder system was presented, which integrated strain sensors and wireless transmission devices as well as created real-time measure axial force and torque in milling and drilling processes. In order to improve the sensitivity of the detection system, an annular groove was cut on the standard commercial tool holder. The Sensors of axial force and torque were arranged in the middle of the annular groove to perceive the minimal deformation in a corresponding direction. The structure of the tool holder was designed by optimization in which the required stiffness is used as the constraint and the detection accuracy is the highest as a target. All of the sensors and other electronic components, such as the data acquisition and the transmitter module and the power module, were integrated with the tool holder as a whole system. The equipment could be clamped on the spindle hole of the milling or drilling machine. A static and dynamic calibration test platform was built, and the static calibration test platform determined the testing performance with a wide range. Cutting tests were performed on a floor type boring-milling machine. The results were consistent and had a high waveform degree of coincidence on the axial force and torque trend compared with the Kistler dynamometer. The results also accurately reflected the axial force and torque changes in dynamic milling and drilling.

INDEX TERMS Force measurement, milling force, real-time monitoring, tool holder, torque measurement, wireless communication.

I. INTRODUCTION

Intelligent manufacturing is a popular development direction in modern cutting. However, the intelligent manufacturing created with this process cannot be separated from the development of machine condition monitoring technology. As one of the most important parameters that can describe the machine conditions and tool status during cutting, cutting force measurements can be used as an important indicator in researching many types of processing[1] such as optimization of cutting parameters [2], [3], monitoring of tool conditions [4]–[6], designing of tool optimization [7], [8], the understanding principles of chip formation [9], detection and suppression of chatter vibrations [10], and prediction of processing surface quality [11]. Thus, in recent years, researchers have proposed a variety of methods to measure the cutting force in turning, milling and drilling.

Initially, some researchers had detected the current or voltage signals of machine tool spindles or other accessories to measure the cutting force indirectly. Auchet *et al.* [12] measured the cutting force by calculating the command voltage of the milling spindle's magnetic bearings. Kim and Kim [13] measured the cutting force by measuring the current of feedback control loops on feed-drive servo motors. These methods usually have a bad versatility. Recently, plate dynamometers are the most commonly used equipment for measuring cutting force because they could provide high precision cutting force measurements and were easy to design and manufacture. Das *et al.* [14] designed a dynamometer based on strain gauge that can measure two dimensional forces and torque in real time of the friction stir welding process. Yaldız *et al.* [15] measured cutting forces and torque by constructing a dynamometer with strain gauge sensors and a piezo-electric accelerometer. Totis *et al.* [16] developed an innovative plate dynamometer to measure triaxial force and torque based on four high-sensitive triaxial piezoelectric force sensors arranged in a novel triangular configuration. However, the plate dynamometers have limits on the size and weight of the workpiece and it was used in the laboratory but not factory in many cases.

Currently, a lot of research has tried to assemble sensors on the tool holder without changing the machine structure. Dini and Tognazzi [17] developed a commercial low-cost rotating dynamometer for the milling process by installing a commercial torque senor in a non-standard part of a standard commercial tool holder, and the signal was transmitted by wireless telemetry. Suprock and Nichols [18], Suprock *et al.* [19] designed a smart tool holder system based on Bluetooth transmission, which modified the tool holder structure to integrated sensors of force and vibration, signal acquisition and the transmitter module. Totis *et al.* [20] developed a rotating dynamometer for the milling process, which used Kistler 9129A piezoelectric triaxial force sensors between the cutter body and the modular cartridge and distributed the force signal transmission by the high-performance telemetry system with 12 channels. Rizal *et al.* [21] designed an innovative integrated rotating dynamometer and tool holder, which arranged strain gauges on symmetrical cross beams to measure the triaxial force in the milling and drill process. Furthermore, he [22] developed a multi-sensor measuring tool holder system for the milling process. Ren *et al.* [23] divided the tool holder into two parts, placed piezoelectric sensors in the middle, and applied bearings to create an in-touch transmission. Xie *et al.* [24] created deformable beams in the tool holder and used capacitive sensors to detect four-component cutting forces, and the data transmitting and power supply was produced using wireless. In addition, he designed an integrated wireless vibration sensing tool holder for tool condition monitoring in the milling process [25]. The aforementioned methods weaken the stiffness of the tool holder, and the analog signal was easy to disturb. Thus, it is necessary to develop the structure of the tool holder to further improve the sensor's sensitivity on the premise that the stiffness meets the design criterion. The force measuring tool holder system should be based on digital wireless signal transmission to provide the tool wear condition monitoring, tool life management, processing quality control, cutting parameter optimization and machine running condition monitoring.

The present study addresses these issues by designing and constructing an integrated smart tool holder system. The paper provides an integrated force measuring tool holder system that can determine the axial cutting force and torque real-time measuring, which has a high sensitivity and meets the requirement for design stiffness. Based on Wi-Fi acquisition and the transmission circuit module, the system has advantages such as long distance transmission, high transmission speed and accuracy. Moreover, the calibration device is designed to complete the wide range cutting force and torque calibration, and the method of calibration only requires putting the system on a standard torque and pressure testing machine. Compared to weight loading, the device reduces the cost of the force measuring tool holder system and the method is easy to operate.

The remainder of this paper is organized as follows. In Section II, the concept and process of the tool holder system design are explained. Section III lists the programs and results of the static, dynamic calibration, and cutting tests. Section IV presents the results and concludes the paper.

II. TOOL HOLDER SYSTEM DESIGN

A. SYSTEM COMPOSITION

In Fig. 1, the composition of the force measuring tool holder system is shown. The perception element is a resistance strain sensor. The signal is transmitted by wireless after the sensor sends it to an acquisition and transmission module. The signal can be received, processed and shown in real-time through the host computer. The whole system needs a power module to supply power, including a resistance strain sensor, acquisition and transmitter module. Therefore, the elements are assembled in a tool holder that contains a resistance strain sensor, modules of acquisition, transmission and power.

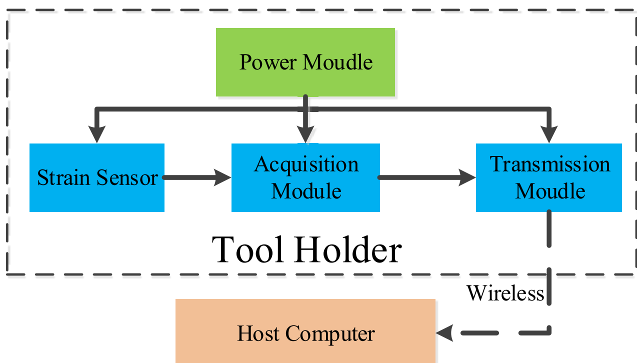

FIGURE 1. Composition of the force measuring system.

B. SENSOR DEVELOPMENT

The tool holder cylinder structure is used as an elastic sensor element. The strain gauges (R_1-R_8) attaching to the cylinder's outer surface and connected to the bridge circuit, as shown in Fig. 2. The strain gauge module of the measuring axial force is BF350-6AA-A (11)-P300, and the torque sensors module is BF350-6HA-B (11)-P300 (Avic Zhonghang Electronic Measuring Instruments Co., Ltd).

Based on the theory of material mechanics and testing technology, the relationships of axial force F_z and torque T with the bridge circuit output voltage U_{F_z} and U_T are deduced

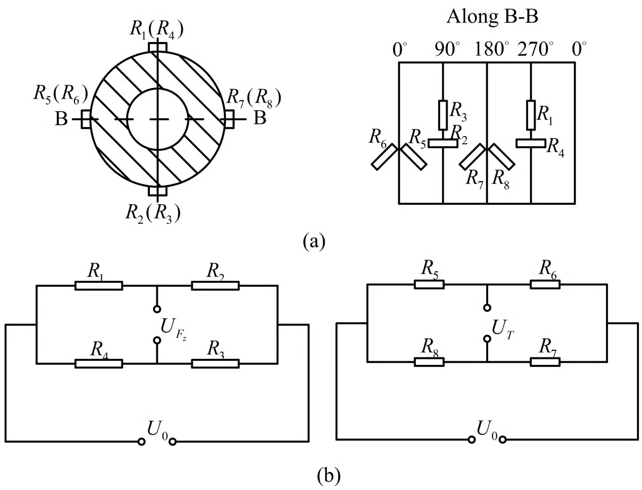

FIGURE 2. Photograph of the (a) strain gauge position; (b) strain gauge connected to the bridge circuit.

as follows:

$$U_{F_z} = -\frac{2U_0K(1+\mu)F_z}{\pi E(D^2-d^2)} \tag{1}$$

$$U_T = \frac{16U_0K(1+\mu)T}{\pi ED^3\left[1-\left(\frac{d}{D}\right)^4\right]} \tag{2}$$

where D and d are the external and internal diameters of the tool holder cylinder structure where the strain gauge is pasted. μ is the Poisson's ratio of the tool holder material; E is the Elastic modulus of the tool holder material; K is the sensitivity coefficient of the strain gauge; U_0 is the supply voltage of the bridge circuit.

C. STRUCTURAL DESIGN

1) ELASTIC ELEMENT DESIGN

In order to improve the sensitivity of the force measuring system, the structure of the standard commercial tool holder should be modified. Specifically, an annular groove is cut on the cylinder where the sensor can be installed, as shown in Fig. 3. The prototype of the standard commercial tool holder used in this paper is a BT50-XW40-150F (Chengdu Chengliang Tools Group Co. Ltd). However, the stiffness of the tool holder will be weakened after the structure is modified. Therefore, the annular groove structural size of the tool holder needs to be optimized to improve the sensitivity of the force measuring system and meet the stiffness requirements.

The first step is to set up the parameter model. As shown in Fig. 3, the structural parameters L_1, L_2, L_3, and L_4 are used as design variables; their initial, lower and upper limit values are set as shown in Table 1.

The second step is to set up the target parameters. We select the static maximum deformation of the X axis (Def_X), static maximum deformation of the Z axis (Def_Z), static maximum rotation around the Z axis (Def_NZ) and equivalent strain at the annular groove (Equa_HXCStrain) as target parameters.

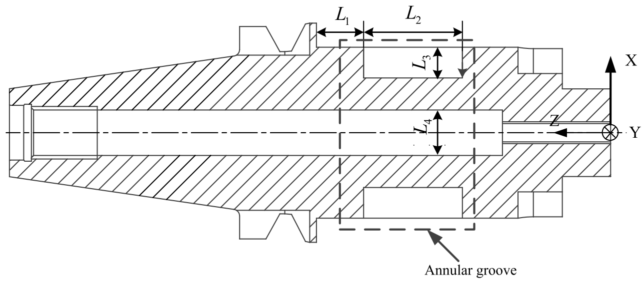

FIGURE 3. Photograph of the modified structure.

TABLE 1. Design parameter of the annular groove on the tool holde.

Parameter	Initial value (mm)	Lower limit value (mm)	Upper limit value (mm)
L_1	16.5	16	20
L_2	45	40	50
L_3	13	10	15
L_4	24	20	24

The third step is to set up the target variable and optimization model. We set the Equa_HXCStrain as the primary target, and the Def_X, Def_Z and Def_NZ values are set to be equal or have greater stiffness values than the design guidelines of the secondary target to be optimized. Then, we establish an optimized mathematical model as follows:

$$\begin{cases} x = (L1, L2, L3, L4)^T \\ \min F(x) = [Def\_X(x), Def\_Z(x), Def\_NZ(x), \\ \qquad Equa\_HXCStrain(x)]^T \end{cases} \tag{3}$$

where x is the column vector of the optimized parameter, which consists of each design variable; $F(x)$ is the target function, which consists of each optimized t component.

The final step is to solve the optimized module. We solve the candidate point with the optimized module by the target-driven optimization method in ANSYS Workbench, and the results are rounded.

Table 2 shows the results comparison of the static characteristics with respect to the tool holder of the optimized model with the original. By comparison with the initial static characteristics, it can be seen from the optimization effect that the strain at the annular groove is increased, and the signal can be perceived more obviously. The sensitivity of the force measuring system is improved. Though the stiffness of the tool holder in the axial, radial and twist directions is weakened, it meets the design criteria requirements.

2) OVERALL SYSTEM DESIGN

The force measuring tool holder system is designed based on the optimized structure of the tool holder, and the system should meet the following design criteria:

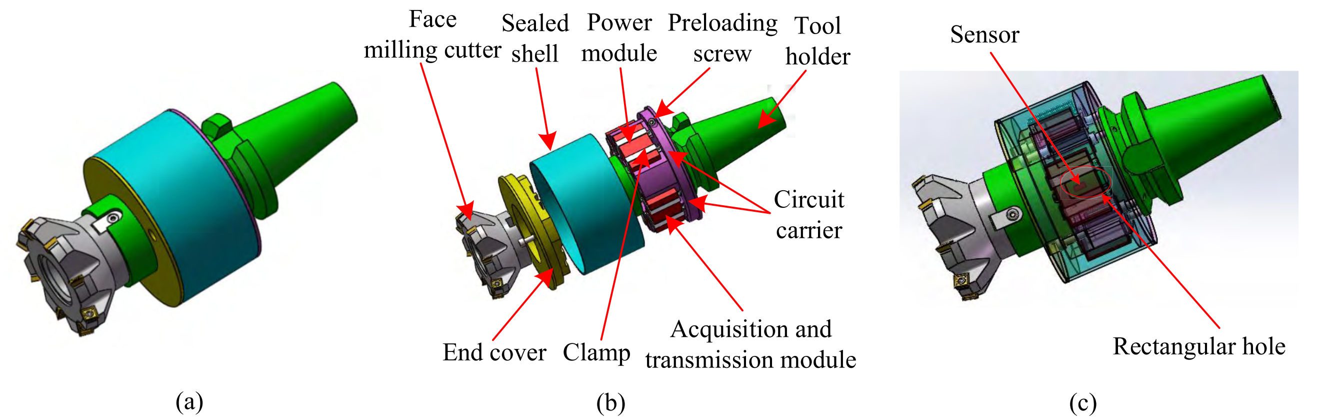

FIGURE 4. System structure (a) assembly diagram, (b) decomposition diagram and (c) location of the sensor

TABLE 2. Results of the static characteristics of the optimized tool holder compared with the original holder.

Static characteristics parameter	Original value	Optimized value	Optimized effect
Def_Total / mm	5.94×10^{-6}	6.99×10^{-6}	+17.67%
Def_X / mm	7.16×10^{-7}	7.52×10^{-7}	+5.02%
Def_Z / mm	5.78×10^{-6}	6.82×10^{-6}	+17.99%
Def_NZ / mm	5.91×10^{-6}	6.97×10^{-6}	+17.93%
Equa_HXCStrain / mm/mm	3.28×10^{-5}	4.20×10^{-5}	+28.05%

a. The stiffness cannot be excessively weakened to affect the performance after the system is assembled.

b. The system should be versatile and should not have any impact on fixing the tool holder onto the machine or clamping the tool onto the tool holder.

c. The dynamic balance should be better.

d. The force measuring system should be easy to install and disassemble to charge to the power module in a timely fashion.

According to the aforementioned design criteria, the force measuring tool holder system is shown in Fig. 4. The circuit carrier contains two similar half-carriers, which places a couple of power modules and acquisition transmission modules, and each can measure a torque or axial force component. In order to ensure its dynamic balance, the power and acquisition transmission modules are disposed on one semi-carrier and the other one symmetrically. Each module is fixed on a semi-carrier by two clamps. Finally, two semi-carriers are held onto the tool holder through two preloading screws, and they can rotate with the tool holder. The sealed end cap is designed to protect the circuit, and it can connect with the circuit carrier through the screw and the integrated part can transmit torque by key. The sensor wire leads to the end of the acquisition and transmission module through the rectangular hole of the circuit carrier groove, and the other end is connected to the power module through a wire.

3) FINITE ELEMENT ANALYSIS

In order to analyze the designed structure's rationality of the force measuring tool holder system, we used finite element software has been used to perform the static and dynamic analysis. The finite element model is a tetrahedral mesh unit, and the unit sizes of the chip, cutter, tool holder, and other accessories are 0.6 mm, 1.5 mm, 2 mm, and 4 mm. The material of the cutter head and the tool holder is 40Cr, and the chip's material is TiCN. The taper shank part of the tool holder was selected to fix, and the static load was along the X, Z, and around the Z direction, and the values of them are 1726N, 3797N and 340Nm, which are obtained by simulation of the actual stress situation of the tool holder in finite element software, as shown in Fig. 5 acted at the tool holder.

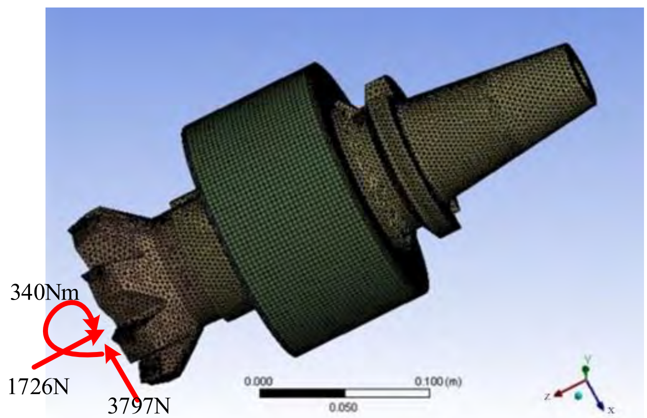

FIGURE 5. Finite element analysis of the force measuring system.

Table 3 shows the results of static and dynamic analysis where the static stiffness of the tool holder is reduced by 18.76%, 22.22% and 30.4% along the X, Z and around the Z direction compared with the standard tool holder. This is mainly due to the annular groove's cut. However, the stiffness still meets the requirements of the tool holder design criteria.

TABLE 3. Result of finite element analysis.

Parameter	Result
Axial stiffness（along the X direction）	4266292 N/mm
Radial stiffness（along the Z direction）	191778 N/mm
Torque stiffness（around the Z direction）	2340000 Nm/rad

D. ACQUISITION AND TRANSMISSION MODULE DESIGN

The composition of hardware in the force measuring tool holder system is shown in Fig. 6 and includes an amplifier circuit, acquisition module, wireless transmission module and power module.

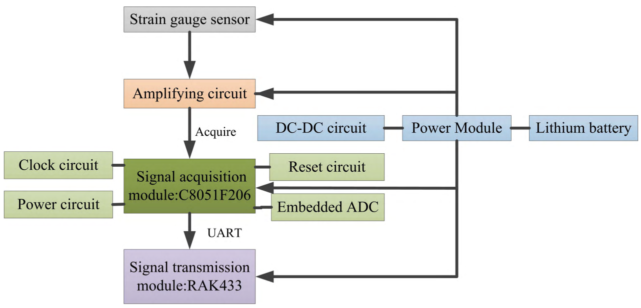

FIGURE 6. Composition of the hardware in the force measuring system.

1) AMPLIFYING CIRCUIT

The signal of the outputting sensor needs to be amplified before it can be converted from analog to digital, because it is very weak at the millivolt level. This paper selects the amplifier instrumentation AD8628 and applies a two-stage amplifier circuit to amplify the signal to the voltage level. The amplifying circuit of axial force signal and the torque signal are shown in Fig. 7

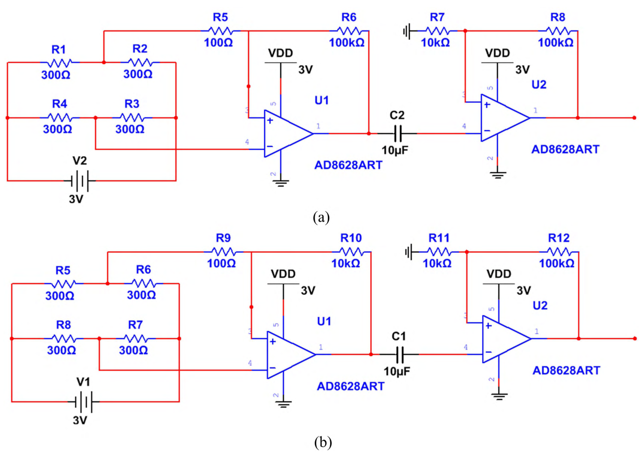

FIGURE 7. Photograph of the amplifying circuit (a) axial force signal and (b) torque signal.

2) ACQUISITION MODULE

According to the parameters of the cutting condition and the tool, the maximum cutting frequency of 300 Hz can be calculated. The sampling rate can be deduced based on the Nyquist sampling theorem. The digital signal can completely restore all of the information from the analog signal only when the sampling rate is more than twice of the maximum frequency of the signal. However, the sampling rate is usually set to 5 to 10 times the maximum frequency of the analog signal. Therefore, the sampling frequency of the acquisition module is set to 1 KHz in this paper. The chip of the module chosen is microcomputer C8051F206. The MCU chip with 12-bit multi-channel ADC is a product introduced by Silicon Laboratories that is fully integrated at a mixed-signal system level. Each device is compatible with the Microcontroller core 8051 and FLASH memory with 8K-byte. The UART and SPI serial interface can be created by hardware. Considering that the signal of the axial force and torque should not affect each other, they can will be collected and transmitted separately. The microcomputer and wireless transmitter module are connected by the UART serial interface.

3) WIRELESS TRANSMISSION MODULE

Commonly, the digital signal transmission methods are Wi-Fi, Bluetooth, Zig-Bee, Infrared and RFID. This paper's transmission method is Wi-Fi because it has some excellent performance abilities such as high transmission communication speed, long transmission distance, and a strong anti-interference ability. In addition, the Wi-Fi module should have a small size so that it can be installed in the limited space of the tool holder. When all of these problems are considered together, this paper selects the ultra-small sized Wi-Fi module RAK433. The module is compliant with 802.11b/ g/ n wireless protocols and supports many protocols such as ARP, IP, ICMP, TCP, UDP, DHCP CLIENT, DHCP SERVER, and DNS with integrating the complete TCP / IP protocol stack. The module is fully able to meet the requirements of the signal transmission rate due to the fact that it supports the highest rate of 921600 bps.

4) POWER MODULE

Most of the lithium batteries are 3.7 V on the market, and each module requires a voltage of 3.3 V. Thus, the DC-DC circuit is required for changing the voltage to a stable 3.3 V. The core chip of DC-DC circuit is LMZ10500, which can convert a range of 2.7 V to 5.5 V into 3.3 V. The circuit connection is shown in Fig. 8.

5) SOFTWARE DESIGN

Software design includes the data acquisition, wireless transmission and the host computer real-time display processing. The main tasks of the software include the following:

a. Collecting the transmitted signal by the amplifier circuit and converting the analog signal into a digital signal.

b. Transmitting the digital signal to the host computer terminal.

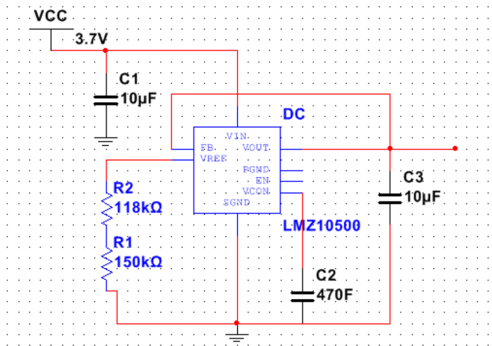

FIGURE 8. Photograph of the DC-DC circuit diagram.

c. Restoring and displaying the digital signal received by the host computer and then storing and analyzing it.

d. Controlling the module of data acquisition and wireless transmission to acquire and transmit work.

In this system, the above parts are programed by DONGHUA Testing TECHNOLOGY CO. LTD. The software is programed using C language that it is developed by an object-oriented visual programming language, Visual C ++ 6.0.

III. TESTING OF THE TOOL HOLDER SYSTEM

A. STATIC CALIBRATION TEST

To obtain the static characteristics of the force measuring tool holder system, the static calibration test is essential [26]. In order to make the result of calibration closer to working conditions, the design program is shown in Fig. 9. When comparing tooling 1 to the machine tool spindle, the taper shank part of the tool holder is fixed in tooling 1 and transmits torque by keys. Likely, tooling 2 is similar to the face milling cutter and the connection with the tool holder is the same as the face milling cutter. The calibration test is set up on a universal testing machine (WDW-50) and torsion testing machine (ND-500, CHANGCHUN KEXIN TEST INSTRUMENT CO., LTD.), as shown in Fig. 10. Through tooling 1, the axial force is based on a method of full scale output (FSO) with an incremental step of 500 N on a standard universal testing machine. Similarly, the torque is applied in incremental steps of 50 N•m through tooling 2 on the standard torsion testing machine. According to the calibration of the experimental data, the static characteristic parameters of the force measuring system can be obtained such as the sensitivity, linearity, repeatability, hysteresis, and cross sensitivity. The result is shown in Fig. 11 and Table 4.

The values in Table 4 show that the sensors of axial force and torque have good linearity, repeatability, and hysteresis. But the axial force resolution is slightly lower. Considering that the specification of the tool holder is BT50, which is suitable for heavy-duty cutting machine tools. Therefore, even though it is slightly lower, it can meet the requirements of actual production and application. The maximum cross sensitivity error of 13.00% occurred on torque T to the axial force F_z, but the other is very small so that it has no effect.

TABLE 4. Static characteristics of the force measuring system.

Static characteristic		Values
Sensitivity	T	1.380×10^{-3} mV/Nm
	F_z	9.537×10^{-6} mV/N
Resolution	T	0.19 Nm
	F_z	28.57 N
Linearity	T	0.51%
	F_z	2.71%
Repeatability	T	0.80%
	F_z	4.76%
Hysteresis	T	0.81%
	F_z	4.71%
Cross sensitivity	$T \rightarrow F_z$	13.00%
	$F_z \rightarrow T$	0.16%

Some compensation measures are required to reduce the maximum cross sensitivity error. Through observing scattered points, which are distributed on both sides of the line and the fitting error by a curve, we can obtain the cross sensitivity curve on torque to axial, as shown in Fig. 12. We subtract the axial force calibration function from the cross sensitivity curve of Fig. 11 and form a new calibration function, which can separate the interference voltage. The axial force can be obtained precisely according to the separation of the interference voltage.

B. DYNAMIC CALIBRATION TEST

For characterizing the operating bandwidth of the force measuring tool holder system, it is necessary to obtain the natural frequency of the system. For this purpose, the dynamic calibration test has been carried out. When the natural frequency of the system is higher than the frequency of the cutting force vibration during the cutting process, the accuracy of the cutting force signal can be ensured. In this paper, the pulse excitation method is used to analyze the modal of the system to obtain its natural frequency. As shown in Figure 13, the system is mounted on the machine spindle and a triaxial accelerometer (1A303E) is connected to the end of the tool holder. The system is energized by using a modal impact hammer (LC02). The input signal (impulsive force) and the output signal (acceleration) are acquired by a signal coupler (DH8300), and the Donghua Dynamic Signal Analysis System (version No. 6.8.25) analyzes the time-domain signals through the a Fast Fourier Transform (FFT). Finally, the test obtains the frequency-amplitude curve of axial force and torque, as shown in Fig. 14 (a) and (b). The results show that the first natural frequency of the direction on axial force is 506.3 Hz and the first natural frequency of the direction on torque is 567.5 Hz.

In this paper, the design of the force measuring tool holder system is to be applied with a spindle speed of 1500 rpm

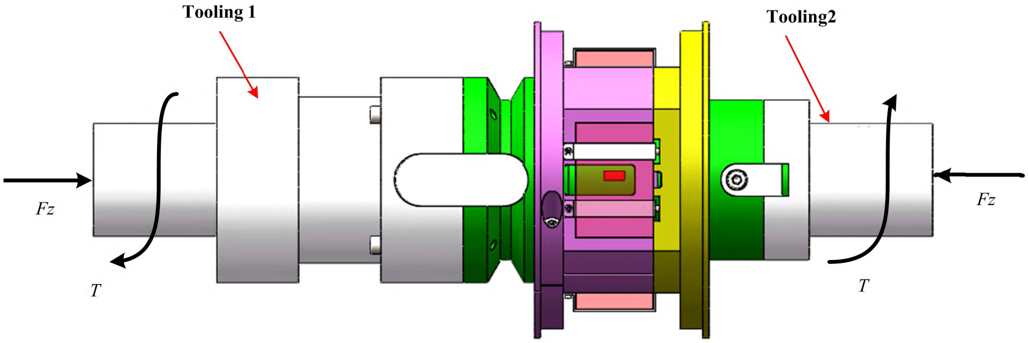

FIGURE 9. Experimental program of static calibration.

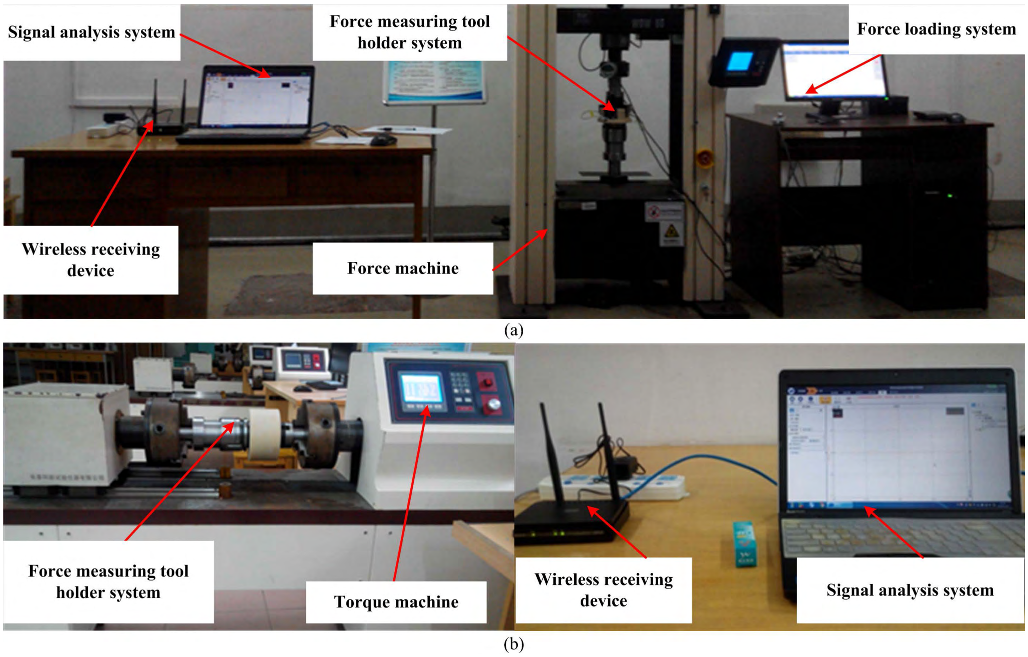

FIGURE 10. Static calibration experimental setup for the (a) axial force test and (b) torque test.

and to have no more than 12 cutter teeth according to the following formula:

$$f_e = Z \cdot \frac{n}{60} \tag{4}$$

where f_e is the cutting force exciting vibration frequency, Z is the cutter teeth number, and n is the spindle speed per minute.

The frequency of the cutting force exciting vibration during the cutting process is calculated by formula (4) as 300 Hz; it is less than the first natural frequency of the force measuring tool holder system to meet the requirements.

C. CUTTING TEST

In order to verify the workability of the force measuring tool holder system, the cutting test was carried out on the vertical milling machine XK5032B (QIQIHAR NO.2 MACHINE TOOL (GROUP) CO., LTD), as shown in Fig. 15-16. The material of the workpiece is carbon structural steel (Q235), and the tool (ISM45-125B) is a 125-mm-diameter indexable face milling cutter with 12 PVD coated carbide inserts (SDKT1204AETN). The reference dynamometer is a multi-component fixed dynamometer (Kistler 9119AA2).

Fig. 17 shows a diagram of the amplitude-frequency characteristics between the two force-measuring devices at a spindle speed of 425 rpm. The results show that the spindle frequency is 7.324 Hz and the tool passing frequency is 84.961 Hz. Thus, these frequencies are lower than the low natural frequency of 506.3 Hz. It indicates that this force measuring system is safe to use in operations below 1500 rpm.

From Fig. 18 ~ 19, some conclusions can be drawn. The force measuring system has a very consistent and high waveform degree coincidence of axial force and torque trend with the Kistler dynamometer. The system can accurately reflect the axial force and torque changes of dynamic milling.

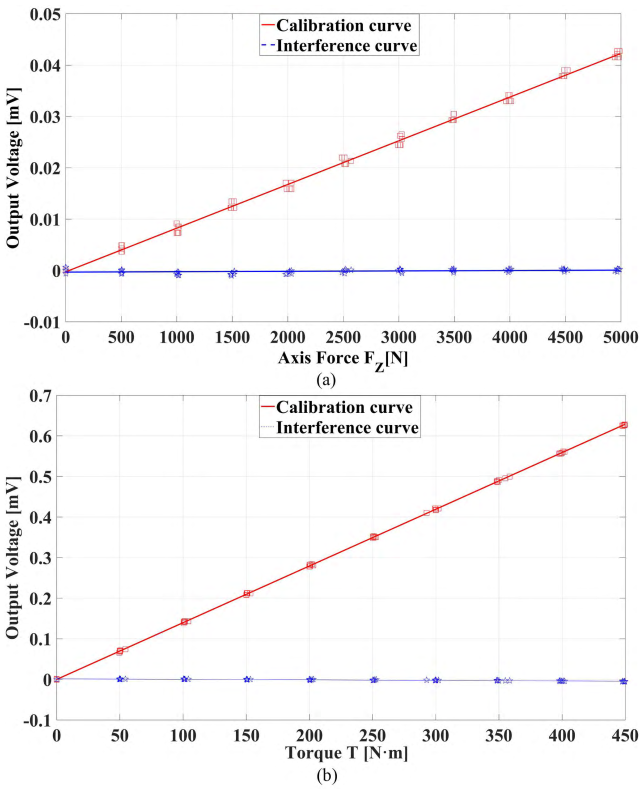

FIGURE 11. Static calibration curve of (a) axial force and (b) torque.

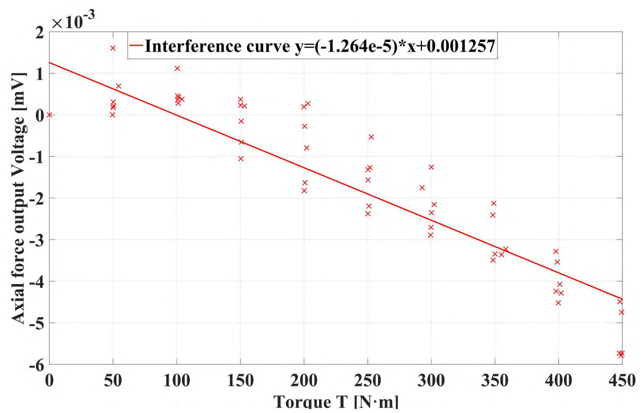

FIGURE 12. Interference curve of torque to axial force after revised.

When the spindle speed is 425 r/min, the feed rate is 150 mm/min and the cutting depth is 2 mm, then the deviation of the average axial force between the force measuring system and the Kistler dynamometer is 7.4% and for the torque, it is 15.3%. And when the spindle speed is 600 r/min, the feed rate is 100 mm/min and the cutting depth is 1.5 mm, then the deviation of the average axial force between the force measuring system and the Kistler dynamometer is 12.9% and for the torque, it is 17.2%. However, they are changed over the same period and the waveform degree coincidence is high.

The method of the reference dynamometer's calculation force and moment is shown in Fig. 20. The reference dynamometer collects the force signal by 3-component

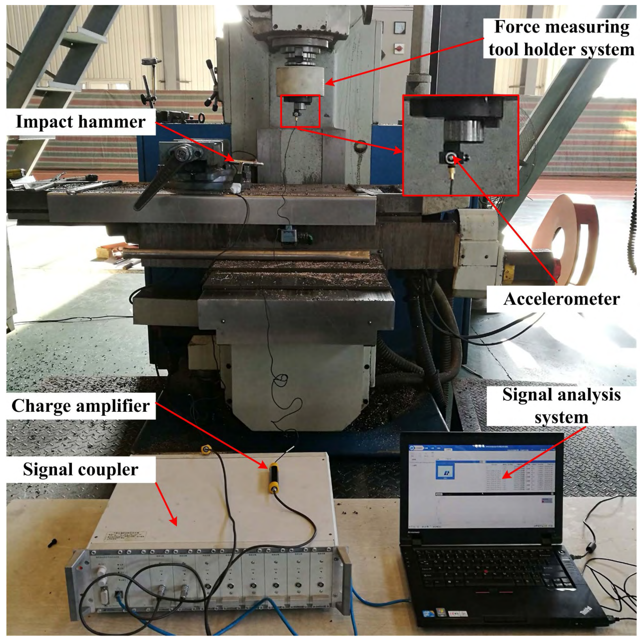

FIGURE 13. Dynamic calibration experimental device.

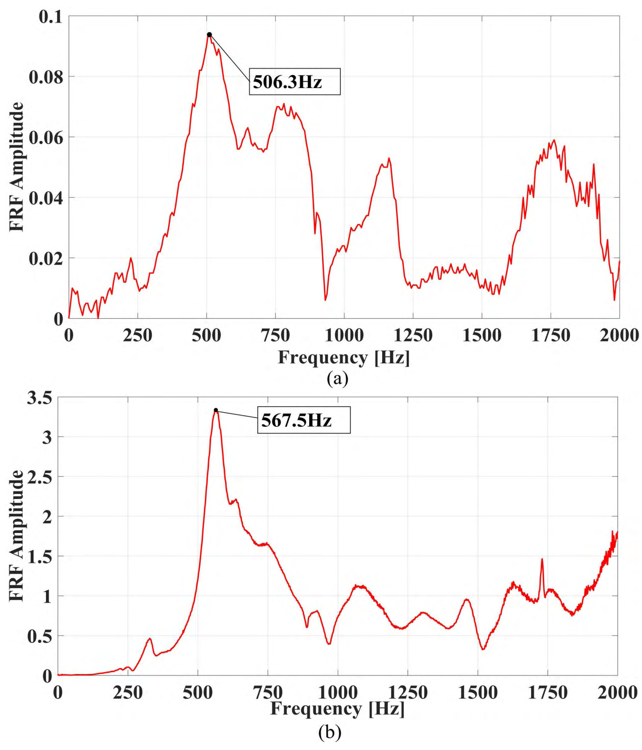

FIGURE 14. Frequency response for the (a) axial force and (b) torque directions.

sensors 1-4, as shown in Fig. 18, and the output is F_{x34}, F_{x12}, F_{y14}, F_{y23}, F_{z1}, F_{z2}, F_{z3}, F_{z4} force signals. Finally, it converts the 8-component output force signal to F_x, F_y, F_z, M_x, M_y, $M_z\,(T)$ according to the following formula:

$$\begin{aligned} F_z &= F_{z1} + F_{z2} + F_{z3} + F_{z4} \\ M_z &= F_{x34} \cdot b - F_{x12} \cdot b + F_{y14} \cdot a - F_{y23} \cdot a \end{aligned} \tag{5}$$

FIGURE 15. Photograph of a completely smart tool holder.

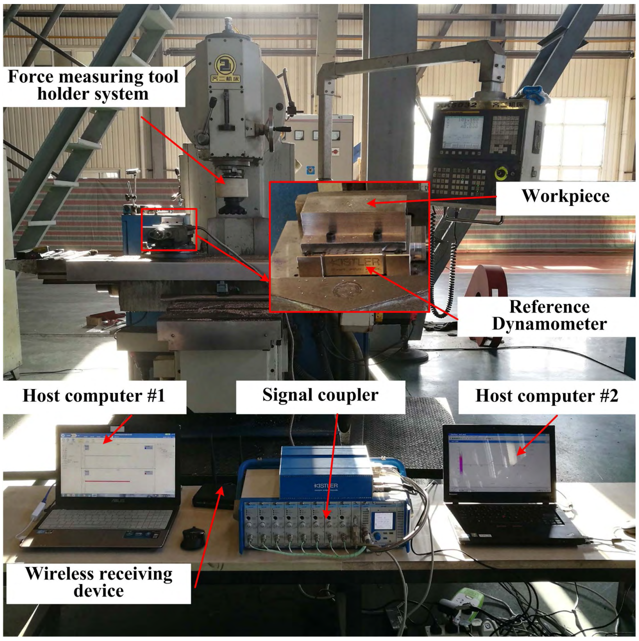

FIGURE 16. Cutting test device.

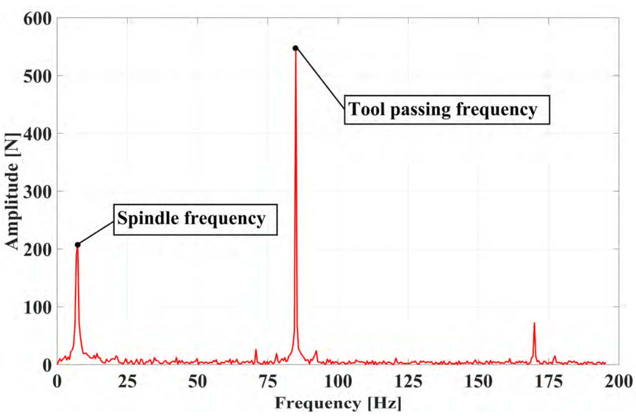

FIGURE 17. Amplitude-frequency characteristic in milling (n = 425 rpm).

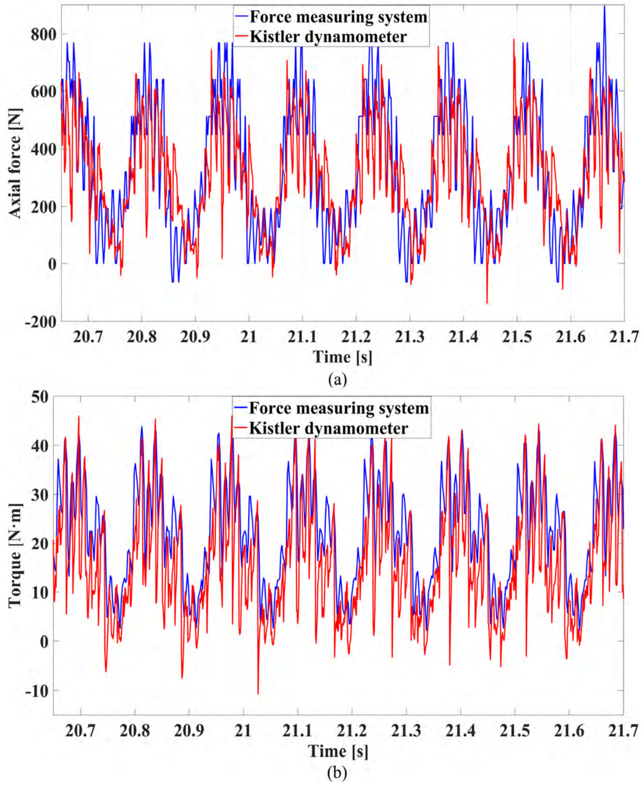

FIGURE 18. Results of the force measuring system and the reference dynamometer on the (a) axial force and (b) torque (n = 425r/min, f = 150mm/min, a_p = 2mm).

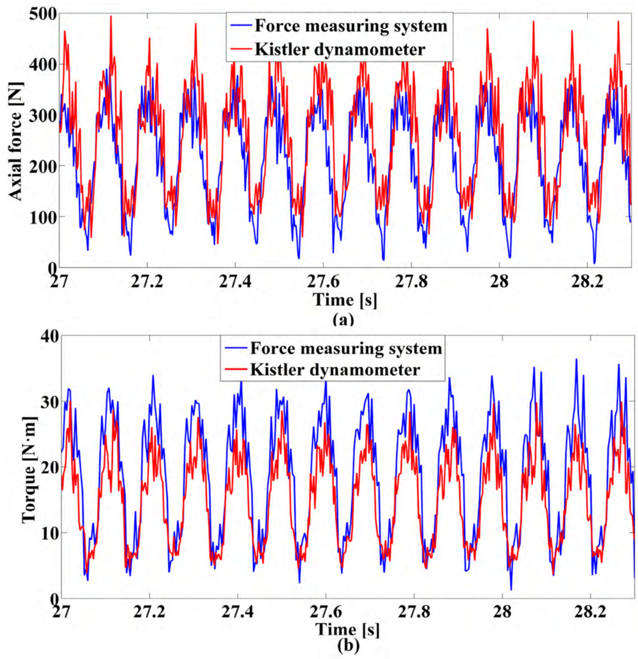

FIGURE 19. Results of the force measuring system and the reference dynamometer on the (a) axial force and (b) torque (n = 600r/min, f = 100mm/min, a_p = 1.5mm).

The force measuring tool holder system is rotating and moving during the cutting process, while the reference dynamometer is fixed. The axial forces (F_z) can be compared directly, but the torque (T) cannot. Due to the fact that the force point B of the workpiece (shown in Fig. 20) changes every moment and does not coincide with point A, it can ensure that the measuring of torque (T) measuring is accurate.

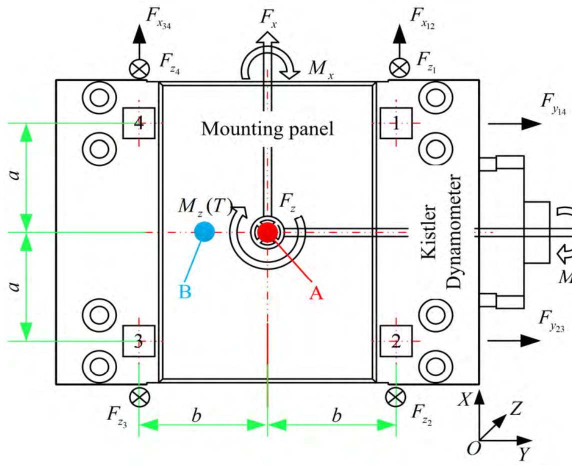

FIGURE 20. Schematic diagram of the reference dynamometer's calculation force and moment.

Therefore, the deviation of the torque between the force measuring system and the reference dynamometer is large.

IV. CONCLUSIONS

In this work, a force measuring tool holder system based on strain gauge sensors for measuring the axial force and torque was designed and developed. The results are summarized as follows:

(1) According to the requirements of the sensor space layout, the detection system sensitivity and tool holder stiffness, the structure of the annular groove where the sensor can be installed is designed through an optimization method. The results show that the sensitivity of the system is increased by 28.05% compared with the initial structure, but the stiffness has been reduced by 5.02%, 17.99%, and 17.93% in the axial, radial, and torsional directions, respectively. However, the results still meet the stiffness requirements for the design guidelines.

(2) The force measuring tool holder system is based on wireless transmission; the structure and mechanical performance of the tool holder are verified to meet the design requirements though the finite element analysis.

(3) By designing the static and dynamic calibration device, we set up the static calibration experimental platform. The static characteristics such as linearity, repeatability and hysteresis are small to 4.7%; the axial force to the torque has a little cross interference and is 0.16%. It can be said that it has almost no effect on the torque measurement. However, the cross interference of torque to the axial force is 13.00%. Constructing the interference separation for error compensation has reduced the influence. The dynamic characteristics show that the first natural frequency is greater than 500 Hz along the directions on axial force and torque.

(4) We set up an experimental cutting platform. The results show that the force measuring system has a consistent and high waveform degree axial force coincidence and torque trend with the Kistler dynamometer. The system can accurately reflect the axial force and torque changes of dynamic milling.

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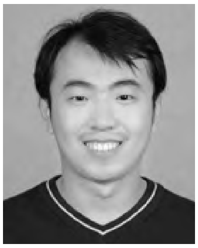

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