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Investigating the Cutting Force Monitoring System in the Boring Process

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Abstract: Due to the closed environment during deep hole boring, it is impossible to observe the working state of the boring bar. Studies show that monitoring the cutting force is the most direct and effective way to reflect the processing status. In this regard, a cutting force monitoring system is designed in the present study for the boring process. The main idea of the designed monitoring system is the piezoelectric effect of the strain gauge. When the tool tip is subjected to the cutting force, the sensor deforms and the strain sensor generates a voltage signal. Accordingly, the cutting force can be obtained by establishing the correlation between the voltage and the applied cutting force. The force of the boring bar and the output of the sensor were analyzed, and an experimental platform for monitoring the boring force was built. This method is applied in a case study and the obtained results demonstrate that the developed cutting force monitoring system has good compatibility, high precision and good dynamic characteristics. It is found that the measurement error of the designed system in the boring process is less than 9.18%, which meets the accuracy requirements of measurements in the dynamic cutting force under machining conditions.

Keywords: Boring bar · Boring processing · Cutting force monitoring

Declarations

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We have no conflict of interest to declare.

Conflicts of interest/Competing interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Availability of data and material

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability (Not applicable)

Authors' contributions

¹ Qiang Liu and Dayong Gao contributed to the conception of the study; Dayong Gao analyzed the working principle of the sensor and the output of the sensor under different cutting forces; Dayong Gao and Ruhong Jia developed a boring force monitoring system and tested its function; Zhou Qiang and Bai Zhengyan designed the structure of the monitoring system and

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optimized it.

Ethics approval

The content studied in this article belongs to the field of metal processing, does not involve humans and animals. This article strictly follows the accepted principles of ethical and professional conduct.

Consent to participate

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1 Introduction

Studies show that in the metal cutting process, real-time monitoring of the cutting status plays an important role in controlling the cutting process, adjusting cutting parameters and detecting tool wear. In this regard, monitoring the cutting force is a direct and effective way to investigate the cutting status. Since the boring process is in a closed state, it is impossible to directly observe the cutting shape and chip color, and it is difficult to monitor the state. The cutting force measurement tools are mostly concentrated in turning and milling processing, and there is less research on boring processing. Currently, numerous cutting force measuring tools, including strain-type cutting force measuring tools [1, 2], piezoelectric cutting force measuring tools [3, 4], capacitive cutting force measuring tools [5] and cutting force measuring tools [6] have been proposed so far. These tools are mainly based on the principle of the surface acoustic wave.

Panzeria et al. [7] designed an integrated tool system that could sense the torsion and bending of elastic elements and obtain the three-way cutting force. Then a strain gauge was installed on an elastic element and finally, the three-way cutting force was decoupled. Rizal et al. [8] developed a strain gauge-based rotary force measuring tool holder and designed a force sensor at the joint between the tool and its holder. The force sensor consisted of four uniformly distributed L-shaped beams and six strain gauges were arranged on each beam. Then the sensor was used to calculate the main cutting force, feed force and the cutting force along the vertical direction. Further investigations reveal that the designed sensor operates accurately for loads and rotating speeds up to 3000 N and 15000 rpm, respectively, which can meet the measurement requirements of the cutting force in engineering milling and drilling processes.

Totis et al. [9] installed a three-way force sensor on the front end of the tool holder and proposed a modular cutting force measurement tool. Through the proposed structure, the cutting blade can be easily replaced without the need to disassemble the force sensor. Accordingly, the commercial sensor and the tool can be structurally integrated so that the cutting force can be measured through a simple structural transformation. Kai Cheng et al. [10, 11] designed a force measuring tool with an integrated piezoelectric film sensor. To this end, they set the sensor between the cemented carbide blade and the shim and applied an appropriate preload to the piezoelectric film to ensure the sensitivity of the measurement. Finally, the perception of the main cutting force was realized, indicating that the entire tool system has a compact structure and a high degree of integration. Luo Ming et al. [12] embedded the Polyvinylidene fluoride (PVDF) piezoelectric film on three contact surfaces behind the milling cutter teeth to measure the cutting force of each tooth during the milling process. It was found that under the action of the cutting force, the PVDF piezoelectric film generates an electric charge, which can be converted into a voltage signal by a charge amplifier. Then an AD conversion was applied to transmit the signal to the upper computer to perform the

required analyses and processing. They showed that the proposed cutter system can effectively identify tool wear and chip formation. Based on the PVDF piezoelectric film, Ma et al. [13] proposed an integrated tool system to monitor the dynamic cutting force and torque during the end milling process. By arranging the PVDF piezoelectric film on the circumference of the cutter bar, the dynamic shear strain of the cutter bar was picked up and the measurement of the cutting force and torque along X- and Y-directions were realized.

Based on a capacitance displacement sensor, Albrecht et al. [14] installed the capacitance displacement sensor on the outer end of the spindle, integrated it and proposed a milling force measurement system. In the proposed system, the cutting force can be indirectly calculated by measuring variations of the gap between the sensor probe and the spindle. Then the influence of the sensor arrangement on the measurement was analyzed and the radial cutting force measurement was completed. Kim et al. [15] used a cylindrical capacitive sensor and proposed a force measuring tool with four structures of 1/4 cylindrical capacitive sensors evenly distributed around the spindle. Then this method was applied in an experiment and X- and Y-components of the cutting force were obtained by measuring the deviation of the spindle along the radial direction. The obtained results showed that the proposed scheme can be effectively applied to measure the cutting force at high speeds.

Stoney et al. [16] proposed a cutting force measurement tool based on the principle of the surface acoustic wave. The surface acoustic wave resonant strain sensor was installed on the upper surface of the tool and the resonant frequency of the sensor was used to obtain a linear correlation with the applied strain. Then the dynamic cutting force was measured during the cutting process. Performed experiments showed that the designed sensor has high sensitivity and linear response to the applied external load and can be effectively applied to measure the main cutting force. Wang Chao et al. [17] installed two surface acoustic wave strain sensors on the upper and side surfaces of the front end of the tool holder and measured the main cutting force and the feed force. Accordingly, it was found that the measurement hysteresis of the main cutting force and the feed force are 7.3% and 4.7%, respectively, where the inter-directional interferences are 20.3% and 13.2%, respectively.

It can be seen from the above that the research on cutting force monitoring is mostly concentrated in turning and milling, while boring force monitoring is less researched. In the present study, it is intended to propose a cutting force monitoring system for a deep-hole boring process. To this end, a measuring device is designed based on the strain performance of the resistance strain gauge. The cutting force is measured by the sensor, and the real-time monitoring function of the system is verified from static and dynamic points of view.

2 Working principle of the monitoring system

The main function of the developed monitoring system in the boring process is to sense and measure cutting force. This system is mainly based on the piezoresistive effect of the sensor. The system consists of a boring bar as an elastic element, a resistive strain sensor as a conversion element and a measurement circuit as a Wheatstone bridge. When the cutting force is applied to the boring bar, the boring bar is deformed, thereby generating stress that affects the sensor resistance in the monitoring system. Finally, an electric signal is produced in the Wheatstone bridge corresponding to the cutting force. In the developed system, a NI signal acquisition card is applied to collect and display signals and Labview software is used to analyze signals and display the real-time cutting force. The composition of the monitoring system is shown in Fig. 1.

Fig. 1 Monitoring system composition

3 Design and analysis of the monitoring system

3.1 Design and installation of the monitoring system

The structure of the monitoring system and the distribution of sensors are shown in Fig. 2. It indicates that four identical sensors (L_1 , L_2 , L_3 , L_4) are used to measure the cutting force. It is worth noting that these sensors operate based on the transverse piezoelectric effect. Accordingly, when a sensor is subjected to a shear force, the applied force can be sensed by variation of the resistance. When the tool tip is subjected to the cutting force (consisting of F_x , F_y and F_z) during the boring process, each sensor produces deforms correspondingly. The strain gauge on each sensor produces the strain signal, which affects the output voltage of the sensor. Then these sensors are collected and processed to obtain accurate cutting force information. Considering small deformation of the sensorsubjected to F_y , the perception is relatively weak so that it is ignored in this article

Fig. 2 Structure of the boring force monitoring system and distribution of the sensors

Studies reveal that the best results can be achieved when the monitoring system is installed close to the fixture at the fixed end. Fig 3 illustrates the clamping configuration. It is observed that the clamping device 1 is connected to the body of the boring bar through a flange, while the clamping device 2 is connected to the sleeve in the tool holder through a flange. When the boring force is applied, a relative displacement occurs between the clamping device 1 and the clamping device 2, which deforms the sensor. On the other hand, the sensor is connected to the signal amplifier and the NI signal acquisition card in sequence followed by the upper computer, where the output voltage signal is processed through Labview software to measure the cutting force.

Fig 3 Configuration and force deformation of the cutting force monitoring system

3.2 Sensor analysis

The working process of the sensor is based on the resistance strain effect. Compared with other strain gauges, the metal foil strain gauge can be made with different sensitivities and shapes, while achieving accurate measurements. These sensors have remarkable advantages, including large allowable current, good flexibility, high fatigue life, small lateral effects, reasonable creep characteristics and ability to withstand large deformations. Accordingly, the metal foil strain gauge is used in the present study as the sensitive component. The strain gauge consists of lead, substrate and sensitive grid. The constantan foil and the sensitive grid are sandwiched between the two substrates. Moreover, the sensitive grid is connected to the measuring circuit by a thick copper wire. Performance of the strain gauge can be adjusted by the metal sensitive grid. This is because the strain gauge works based on the strain effect of the metal, where the resistance of the sensitive grid to the changes originates from mechanical deformations of the sensitive grid wire under the action of external force. Resistance R of a piece of metal wire with a length L and a cross-sectional area A can be expressed as the following:

$$R = \rho \frac{L}{A} \quad (1)$$

When the length of the wire changes under the action of the external force, thereby affecting the corresponding cross-section area and the resistivity. In this regard, variations of the resistance can be expressed in the form below:

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A} \quad (2)$$

For example, the cross-section area of a circular wire with a radius r is $A = \pi r^2$ and $\frac{\Delta A}{A} = \frac{2\Delta r}{r}$. Since the wire is within the elastic range $\frac{\Delta L}{L} = \varepsilon$, $\frac{\Delta r}{r} = -\lambda \varepsilon$ and $\frac{\Delta \rho}{\rho} = \lambda \sigma = \lambda E \varepsilon$. Substituting these expressions in equation (2) results in the following expression:

$$\frac{\Delta R}{R} = (1 + 2\mu + \lambda E) \varepsilon \quad (3)$$

Where ε is the longitudinal strain of the metal wire, which is usually measured by a microstrain; μ is the Poisson's ratio of the metal wire material, which is usually between 0.3 and 0.5 for copper; λ is the piezoresistance coefficient of the metal wire; σ is the stress value of the strain gauge wire; E is the elastic modulus of the metal material. It should be indicated that ε , μ , λ , σ , and E have constant values for each material. Accordingly, a new constant $K_0=1+2\mu+\lambda E$ can be introduced. Consequently, equation (3) can be rewritten in the form below:

$$\frac{\Delta R}{R}=K_0\varepsilon \quad (4)$$

Equation (4) indicates that the relative change of the strain gauge resistance only depends on the constant K_0 and the longitudinal strain ε of the strain gauge resistance wire. For a constant longitudinal strain ε , the greater the constant K_0 , the greater the relative change of the strain gauge resistance, and the more sensitive the strain gauge. Relative variations of the strain gauge resistance are proportional to the longitudinal strain ε of the resistance wire. This can be mathematically expressed as the following:

$$\frac{\Delta R}{R}=K\varepsilon \quad (5)$$

Where K is the sensitivity coefficient of the resistance strain gauge.

In the performed experiments, the bridge circuit connection method of the strain gauge is used to improve the sensitivity and linearity of the sensor. To this end, two strain gauges with the same properties are connected to the opposite sides of the bridge, and the two adjacent strain gauges have different force properties. Under this circumstance, $R_1=R_4=R+\Delta R$, $R_2=R_3=R-\Delta R$. Fig. 5 presents the configuration of the bridge circuit. When the tool tip is forced, the sensitive grid is strained by the external force, the resistance of the sensitive grid changes and the Wheatstone bridge loses the original balanced output voltage. The output voltage of the sensor is directly correlated with the applied force on the tool tip. Accordingly, the cutting force can be effectively measured by arranging the sensitive grid.

Fig. 5 Configuration of a Wheatstone bridge circuit

Introducing a voltage source U_i to the Wheatstone bridge circuit, the output of the bridge circuit is:

$$U_o=U_{AB}-U_{AD}=\frac{R_1}{R_1+R_2}E-\frac{R_3}{R_3+R_4}E=\frac{R_1R_4-R_2R_3}{(R_1+R_2)(R_3+R_4)}U_i \quad (6)$$

Substituting $R_1=R_4=R+\Delta R$, $R_2=R_3=R-\Delta R$ into equation (6) yields the following expression:

$$U_o = U_i \frac{(R + \Delta R)^2 - (R - \Delta R)^2}{2R \cdot 2R} = U_i \frac{\Delta R}{R} \quad (7)$$

Meanwhile, substituting equation (5) into equation (7) can get:

$$U_o = U_i \cdot K \varepsilon \quad (8)$$

Equation (8) indicates that the output voltage U_o of the bridge circuit built by the strain gauge is related to the input voltage U_i , sensitivity coefficient K of the strain gauge and the strain ε . When U_i and K are constants, then the output voltage of the bridge circuit is proportional to the strain ε , thereby achieving the purpose of the force measuring. Schematic of the sensor and the parameters are shown in Fig. 6 and Table 1.

Fig. 6 Resistance strain sensor

Table 2 Resistance strain sensor parameters

Parameter	Numerical value
Range	100g
Input impedance	1090±10Ω
Output impedance	1000±10Ω
Precision	0.03%
Sensitivity	0.6±0.15mv/V
Creep	0.05%F.S/30min
Insulation resistance	≥2000MΩ
Excitation voltage	3~10VDC
Operating temperature range	-10°C~+55°C
Hysteresis	0.02%F.S
Safe overload range	120%F.S

3.3 Analyzing the sensor output for different cutting forces

When the cutting force F_x is applied, the sensing unit is subjected to bending stress. Fig. 7 shows that in this case, the L_1 and L_3 sensors are subjected to compressive and tensile stresses, respectively. The magnitude of the compressive and tensile stresses are the same and the direction is opposite. Considering the symmetrical arrangement of sensors, the voltages generated by L_1 and L_3 are equal in magnitude and have a positive and negative correlation with the zero voltage, respectively.

Fig. 7 Force analysis of the monitoring system subjected to the cutting force F_x

When a force F_x is applied, a bending deformation occurs in the boring bar. For a boring bar with a length l and a thickness of the monitoring system x , the coordinate system can be established where the center point of section C is the origin of the coordinate. Then the bending moment can be calculated as the following:

$$M(x) = F_x(l - x) \quad (9)$$

Then the approximate differential equation of the torsion curve is:

$$EI \omega'' = M(x) = F_x(l - x) \quad (10)$$

Integrating equation (10) results in the following equation:

$$EI \omega' = -\frac{F_x}{2}x^2 + F_x l x + C \quad (11)$$

$$EI \omega = -\frac{F_x}{6}x^3 + \frac{F_x l}{2}x^2 + Cx + D \quad (12)$$

Since section C is a fixed end, the rotation angle and deflection are zero, that is, when $x=0$, $\omega'_c = \theta_c = 0$, $\omega_c = 0$. As a result, $C = EI \theta_c = 0$, $D = EI \omega_c = 0$. Substituting these terms into equations (xx) and (xx), the rotation angle and deflection at the center point of section B can be expressed as the following:

$$\theta_B = \omega'_B = \frac{1}{EI} \left(-\frac{F_x}{2}x^2 + F_x l x \right) \quad (13)$$

$$\omega_B = \frac{1}{EI} \left(-\frac{F_x}{6}x^3 + \frac{F_x l}{2}x^2 \right) \quad (14)$$

Where E is the modulus of elasticity and I is the moment of inertia of the section.

Deformation at the center point of section B deforms the sensor, thereby generating a strain in the sensor. There is a proportional correlation between the sensor deformation and the strain. Accordingly, the deformation of the rod body is proportional to the strain ε of the sensor:

$$\varepsilon = k \omega_B \quad (15)$$

Where k is the conversion coefficient between the deformation at the center point of section B and the strain of the sensor, which can be obtained through experiments. The output voltage U_{F_x} of the sensor L_3 subjected to the force F_x is:

$$U_{F_x} = U_i K k f_B = \frac{U_i K k}{EI} \left(-\frac{F_x}{6} x^3 + \frac{F_x l}{2} x^2 \right) \quad (16)$$

Since the voltages generated by L₁ and L₃ are equal in magnitude. Therefore, the voltage of L₁ can be expressed as $-U_{F_x}$, and the voltage output of L₂ and L₄ is zero.

Fig 8 shows the boring bar subjected to the cutting force F_z . Similarly, the generated voltage by the L₂ sensor originating from the cutting force can be expressed as:

$$U_{F_z} = U_i K k f_B = \frac{U_i K k}{EI} \left(-\frac{F_z}{6} x^3 + \frac{F_z l}{2} x^2 \right) \quad (17)$$

Since the voltages of the L₂ and L₄ sensing units are equal and opposite in sign, the voltage generated by the sensing unit L₄ can be expressed as $-U_{F_z}$. In this case, the output voltage of L₁ and L₃ is zero.

Fig. 8 Force analysis of the monitoring system subjected to the cutting force F_z

4 Static calibration experiment

In order to calibrate the monitoring system, the static calibration is realized by loading the standard weight at the tool head. The boring bar with monitoring function is clamped on the tool holder, gravity load is applied at the tool head, and the high-precision sensor is used for calibration. Based on previous experiences, the measuring range of the sensor is set to 0-800N.

4.1 Calibration results along F_z direction

According to the previous analysis, when the weight is loaded at the front end of the boring bar along the F_z direction, theoretical output value of the interference sensor (L₁, L₃) perpendicular to the measuring sensor (L₂, L₄) approaches zero. However, a deviation was observed in this regard. More specifically, the actual output of the strain sensor approached the lateral interference of F_z to F_x , and the average value of the output voltage of sensor L₁ and sensor L₃ was $U_{13} = (U_1 - U_3)/2$. After processing by the monitoring system, the output analog quantity is obtained and then the discrete points are linearly fitted by the least square method. Fig 9 shows the static calibration and interference curves. Combined with the concept of lateral interference, the interference degree is 6.8%.

Fig 9 Static calibration curves of F_z

Based on the following expressions, the calculated linearity and repeatability of F_z direction are $\delta L=2.4\%$, $\sigma R=1.2\%$, respectively.

$$\delta_L = \frac{|\Delta_{\max}|}{Y_{FS}} \times 100\% \quad (18)$$

$$\sigma_R = \frac{|\Delta y_{RM}|}{Y_{FS}} \times 100\% \quad (19)$$

4.2 Calibration result along the F_x direction

According to the previous analysis, when the mass block is loaded at the front end of the boring bar along the F_x direction, theoretical output value of the interference sensor (L_2 , L_4), which is perpendicular to the measuring sensor (L_1 , L_3), approaches zero. However, there a deviation was observed in the experiment. More specifically, the actual output value of the strain sensor at this direction is the lateral interference of F_x to F_z . The data obtained after processing the output voltage of sensor L2 and sensor L4 is based on the principle of least squares. Fig. 10 illustrates the interference curve by MATLAB software, indicating that the interference degree is 6.1%.

Fig 10 Static calibration curves of F_x

Based on equations (18) and (19), the linearity and repeatability of F_x direction can be calculated as $\delta_L=2.2\%$, $\sigma_R=1.1\%$, respectively.

The static performance indicators of the sensor are shown in Table 2. It is found that there is good linearity between sensors along F_z and F_x directions. Meanwhile, the repeatability is good and does not exceed 2%. The lateral interference degree of F_z to F_x is 6.8%, while the lateral interference degree of F_x to F_z is 6.1%, which meets the design requirements.

Table2. Static performance indices of the sensor

Components of the Cutting Force	Static Performance Indexes			
	Linearity Error	Repeatability Error	Cross-Interference Error	
			F_z	F_x
F_z	2.4%	1.2%	-	6.8%
F_x	2.2%	1.1%	6.1%	-

5. Performance test of the monitoring system

Fig 11 shows the configuration of the testing platform. A desktop dynamometer (Kistler 9139AA) was installed on the workbench selected as the reference dynamometer, and the collected force signal was used as the reference force. During the test, the cutting force signal was collected and saved by the upper computer software of the monitoring system, and the reference force was collected and saved by the charge amplifier and Kistler DynoWare software at the same time. The sampling frequency was set to 100 Hz. By analyzing and comparing the force signals in various directions, the performance of the monitoring system was evaluated.

Fig 11 Configuration of the test device to evaluate the performance of the monitoring system

It should be noted that due to the different material properties of the designed monitoring system and the dynamometer, the materials used in the sensors deform significantly after being stressed so that a certain recovery time is required. Accordingly, a certain error is unavoidable in the measurement results. In this experiment, static loading, static loading-unloading, impact

loading and continuous loading were used to verify the feasibility of the system's F_x and F_z direction cutting force and signal monitoring functions.

5.1 Static loading

In the static loading experiment, a weight of 20Kg is loaded to the cutter head and after reaching stability, data acquisition begins by the two systems. Then the monitoring system is rotated 90° and the same operation is carried out to obtain the force of the tool bar in the F_x and F_z directions. After the processing, the force signals collected by the four sensors and the signals collected by the force gauge are compared. In this regard, Fig. 12 shows the obtained results. For a steady load, the obtained force from the dynamometer is about 196N. Moreover, the maximum values of F_x and F_z directions and the corresponding errors are 214N and 212N, and 9.18% and 8.16%, respectively. Fig. 12 indicates that the data collected by the monitoring system fluctuates relative to the data obtained by the force gauge. These fluctuations mainly occur when the monitoring system receives a certain impact force after loading, leading to an increase in the measurement result. Then the measurement result gradually decreases and becomes stable. After stabilization, the measurement error decreases, but this process requires a certain recovery time.

Fig 12 Comparison of the collected signals from different sensors subjected to a static loading:

(a) sensor L_1 , (b) sensor L_3 , (c) sensor L_2 and (d) sensor L_4

5.2 Static loading-unloading

Static loading-unloading is similar to the static loading test method. Furthermore, a 20Kg weight is used for loading, and then it is unloaded immediately. After reaching stability, the force of the tool bar in the F_x and F_z directions is measured. After processing, the force signals collected by the four sensors and the force gauge are compared and the obtained results are shown in Fig 13. It is observed that the amplitudes measured by the two methods are similar, and the loading-unloading process is

detected in both schemes. The measured value by the dynamometer is 196N, indicating a deviation from the measured value. It is found that the maximum measured values in F_x and F_z directions, and the corresponding maximum errors are 210N and 213N, and 7.14% and 8.67%, respectively. After unloading, the monitoring system is not completely reset to zero, and there is a drift phenomenon.

Fig 13 Comparison of the collected signals from different sensors during the static loading-unloading:

(a) sensor L_1 , (b) sensor L_3 , (c) sensor L_2 and (d) sensor L_4

5.3 Impact loading

In this section, the impact loading method is used to verify the dynamic performance of the monitoring system. When both systems become stable, an impact force is applied to the cutter head of the boring bar and the received forces from sensors along F_x and F_z directions and the force gauge are compared. Fig 14 shows the obtained results in this regard. According to the waveform diagram, it is found that when a single impact is applied to the boring bar, the monitoring system can maintain a good measurement trend with the force gauge. The maximum values of the tip point in the F_x direction measured by the force gauge and the monitoring system are 269N and 292N, respectively, and the maximum error is 8.55%. Moreover, the maximum values measured by the force gauge and the monitoring system in the F_z direction are 272N and 296N, respectively, indicating that the maximum error is 8.82%. After the impact, the monitoring system still drifts.

Fig 14 Comparison of the collected signals from different sensors during impact loading test:
(a) sensor L_1 , (b) sensor L_3 , (c) sensor L_2 and (d) sensor L_4

5.4 Continuous loading

The main purpose of the continuous loading experiment is to verify the accuracy of the dynamic measurement after the boring bar is subjected to multiple impacts. Similar to the impact loading method, the boring bar is continuously loaded with the impact force multiple times, and the received force by the F_x and F_z direction sensors is obtained. Then the processed data with the collected data by the dynamometer are compared. In this regard, Fig 15 shows the final waveform graph curve. It is observed that when the boring bar is continuously impacted, the measurement of the monitoring system during unloading has large fluctuations and the drift phenomenon is obvious. However, measurement errors during the loading process are not large. After processing four loadings in the F_x direction, it is found that the average force values obtained from the force gauge and the monitoring system are 240N and 262N, respectively, indicating an average error of 9.17%. Furthermore, after processing four loadings in the F_z direction, the average force values obtained from the dynamometer and the monitoring system are 234N and 255N, respectively, indicating an average error of 8.97%. The overall trend of the collected signal meets the measurement requirements.

Fig. 15 Comparison of the collected signals from different sensors during the continuous loading:

(a) sensor L_1 , (b) sensor L_3 , (c) sensor L_2 and (d) sensor L_4

The summary of experimental results is shown in Table 3 and Figure 16. It is observed that there is a certain difference between the measurement results of the monitoring system and that of the dynamometer. However, deviations are less than 10%, and the trends are the same. Various factors, including the pre-tightening state and installation accuracy of the two sensors affect the measurement results. Moreover, it is found that the force of the monitoring system does not return to zero after the load completion. This phenomenon may be attributed to the signal drift and material characteristics of the sensor. Further investigations reveal that many factors affect the sensor drift. In the present study, the sensor drift was determined by the sensing structure and assembly problems of the monitoring system. Therefore, more uncertainties and recognition errors may be generated. Furthermore, it is a challenge to avoid the drift problem. However, the measurement results in the experiment are not much different, indicating that the monitoring system can reliably collect the information of the cutting force on the boring bar, and it has good application performance.

Table 3 Summary of measurement results of the monitoring system and Kistler dynamometer

	Force	Monitoring System	Kistler dynamometer	Measurement error
Static loading	$F_x(N)$	214	196	9.18%
	$F_z(N)$	212	196	8.16%
Static loading-unloading	$F_x(N)$	210	196	7.14%
	$F_z(N)$	213	196	8.67%
Impact loading	$F_x(N)$	292	269	8.55%
	$F_z(N)$	296	272	8.82%
Continuous loading	$F_x(N)$	262	240	9.17%
	$F_z(N)$	255	234	8.97%

Fig 16 Performance of monitoring system at different conditions

6 Conclusions

Aiming at the current problems in cutting force measurement in the boring process, a cutting force monitoring system is proposed in the present study. To this end, the installation position of the system and parameters of the sensors are introduced. Analyzed the working principle of the sensor and the output of the voltage when the force was applied, and set up a boring force monitoring experiment platform. A static calibration was carried out on the monitoring system, and then the static and dynamic performance of the monitoring system was verified through comparative experiments, including the static loading, static loading-unloading, impact loading and continuous loading tests. Based on the obtained results, it is found that the measured data by the designed monitoring system is consistent with the collected data by the dynamometer, which can realize the measurement of the main cutting force. The measuring error is less than 9.18%, demonstrating the feasibility of the system's measurement performance. In addition, this part of the research will also be applied to the state monitoring of intelligent damping boring bars.

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