Research and Application of PVDF Piezoelectric Film Accelerometer

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Abstract: PVDF piezoelectric film accelerometers can detect vibration signals due to their sensitive piezoelectric material components. Addressing the issues of low sensitivity and narrow frequency range in existing vibration monitoring sensors for turning processes, this paper proposes a PVDF piezoelectric film accelerometer based on a vertical compression structure. First, the mechanical model of the sensor under working conditions is established, analyzing the structural and material performance parameters related to its natural frequency and sensitivity. An ANSYS finite element model is built, and modal and harmonic response analyses of the model are performed. Simulation results show that the designed sensor's operating frequency and sensitivity can meet the requirements for vibration testing in turning. Calibration experiments on the sensor demonstrate that its natural frequency is 8900 Hz, its operating frequency range is 0.5-2900 Hz, and its charge sensitivity is 25.284 pC/(m·s^{-2}). The sensor features a wide frequency range and high sensitivity, enabling its use for detecting vibration signals in turning experiments.

1. Introduction

With the development of modern technology, a new generation of industrial technology with intelligent manufacturing as the core promotes the transformation of "Made in China" to "Creation in China". When cutting difficult-to-machining materials, tool wear is a key factor affecting the processing accuracy, production efficiency and manufacturing cost of parts. Monitoring vibration signals during cutting and processing is an important method to monitor tool wear. The acceleration sensor is the core component of the monitoring system and can effectively judge the wear status of the tool based on the monitoring results. Therefore, the preparation and calibration of the acceleration sensor have both important theoretical significance and engineering application value.

In 2011, Huang Yijin[1]studied a seismic detector using PVDF materials, using cantilever beams and reverse compression structures, with a physical test voltage sensitivity of 21mV/ms^{-2} and a frequency range of 5-45Hz. In 2016, Klaas et al[2]. designed a new PVDF vibration sensor composed of polymer blocks and two lead attachments. The simulation shows that the strain and charge peak amplitude are consistent well, but the actual collision test cost is high. This idea can improve the versatility of the sensor. In 2016, Vinh Nguyen et al[3]. designed the PVDF piezoelectric thin film strain sensing system to monitor turning dynamic cutting force, torque and boring modal coupled flutter. In 2017, Yan Ming[4]developed a health monitoring method for high-voltage transmission towers. The core is to capture natural excitation displacement waveforms through PVDF sensors, compare the differences in the characteristics of health and damage waveforms, and use natural frequency changes to identify structural damage. Voltage sensitivity is 24mV/ms^{-2}, nonlinear error is 5.4%, frequency range is 2-45Hz. In 2018, Mao Shijie[5]designed a plane shear piezoelectric accelerometer with PZT-5A, and the finite element analysis natural frequency was about 15kHz and the sensitivity was 100mV/g. In 2018, the triangular shear piezoelectric accelerometer developed by Lumin[6]reached 8000Hz, had a sensitivity of 41pC/g, and was resistant to high impact and high temperatures. In 2019, Wei, Li[7]proposed a two-dimensional FBG accelerometer based on multi-axis curved hinges. Max-sensor is stable with a frequency band of 5-170Hz, acceleration sensitivity is 220pm/g, cross-interference between the two directions is <4%, and resonant frequency is 279.2Hz. Min-sensor has a flat range of 20-600Hz, acceleration sensitivity of 40pm/g, cross interference <3.5%, and resonant frequency of 814.3Hz. In 2021, Jiang Shuaishuai[8]designed a triangular shear piezoelectric acceleration sensor. Calibration and micro-seismic signal detection tests show that micro-seismic signals can be detected when the resonant frequency is 6300 Hz, the operating frequency is 0.1-2100 Hz, and the charge sensitivity is 34.626pC/(m·s^{-2}), with wide band and high sensitivity. In 2024, the electromagnetic MEMS vibration sensor studied by Zhu Xu[9]has a natural frequency of 66 Hz, which can achieve 63-69 Hz vibration measurement within the range of 0-3 g, with a sensitivity of 263 mV/g and a linearity of 99.8%.

This paper designs a PVDF piezoelectric thin film acceleration sensor with a vertical compression structure. A sensor mechanics model was established, the sensor structure was designed and the materials were selected; ANSYS software was used to analyze the rationality of the design structure, natural frequency and resonant frequency; a vibration experiment platform was built to calibrate and turn the designed sensors to verify the correctness of the design scheme, theoretical calculation and simulation analysis.

2. Sensor mechanical model

The mechanical model of PVDF piezoelectric thin-film acceleration sensor is shown in Figure 1, its base rigidly fixed on the reference plane of the measured mechanism, and the dynamic model can be equivalent to a second-order vibration system with a single degree of freedom, where *m* is the mass of the mass block, y_i is the basic displacement of the ground, y_0 is the relative motion displacement of the inertial mass block relative to the base, *k* is the stiffness coefficient, and *c* is the damping coefficient.

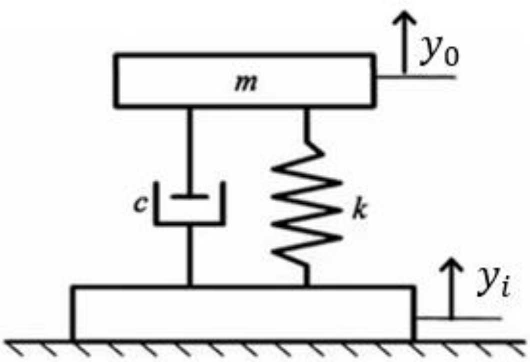


Fig.1 Sensor mechanics model

The dynamic response characteristic of the sensor is equivalent to the dynamic relationship between the output displacement y_0 and the input acceleration *a*. According to the equivalent dynamic model, the governing differential equation of motion is established as:

$$m\ddot{y}_0(t) + c\dot{y}_0(t) + ky_0(t) = -m\ddot{y}_i(t) = -ma \tag{1}$$

The fourier transform of equation (1) can be obtained:

$$m(j\omega)^2 y_0(\omega) + c(j\omega)y_0(\omega) + ky_0(\omega) = -ma \tag{2}$$

Where ω is the forced vibration frequency.

$$\frac{y_0(j\omega)}{a} = -\frac{m}{m(j\omega)^2 + c(j\omega) + k} = -\frac{1}{(j\omega)^2 + c(jw)/m + k/m} \tag{3}$$

Let the natural frequency of the sensor $\omega_n = \sqrt{k/m}$, the damping ratio $\zeta = c/(2\sqrt{km})$, and the substitution (3) can obtain:

$$\frac{y_0(jw)}{a} = -\frac{(1/\omega_n)^2}{1-(\omega/\omega_n) + 2\zeta(\omega/\omega_n)j} \tag{4}$$

The relationship between the displacement of PVDF piezoelectric film and the vibration acceleration of the datum of the measured mechanism is as follows:

$$\left|\frac{y_0}{a}\right| = \frac{1}{\omega_n^2 + \sqrt{\left[1-(\omega/\omega_n)^2\right]^2 + (2\zeta\omega/\omega_n)^2}} \tag{5}$$

At a specific vibration frequency, the inertial force exerted by the proof mass on the piezoelectric element is an alternating stress. Since the motion of the proof mass is governed by Newton's second law, this force is proportional to the acceleration it experiences, that is $f = ma$.

Under the precondition of preload fixation, the charge quantity Q generated by the piezoelectric element is proportional to the applied force f:

$$Q = d_{ij} f = d_{ij} ma = d_{ij} k y_0 \tag{6}$$

Where d_{ij} is the piezoelectric constant of PVDF piezoelectric film. According to equations (5) and (6), the charge sensitivity coefficient of the sensor is:

$$K_Q = \left|\frac{Q}{a}\right| = \frac{d_{ij}k}{\omega_n^2\sqrt{\left[1-(\omega/\omega_n)^2\right]^2 + (2\zeta\omega/\omega_n)^2}} \tag{7}$$

According to Equation (7), when the excitation frequency of the piezoelectric accelerometer is much lower than its natural frequency, that is, $\omega \ll \omega_n/3$, the approximation $K_Q = d_{ij} \cdot k/\omega_n^2$ holds. The sensitivity of the sensor is proportional to the piezoelectric constant and inversely proportional to the natural frequency. In designing a piezoelectric accelerometer, it is necessary to balance these two key parameters: sensitivity and resonant frequency. Methods to increase sensitivity include selecting materials with a high piezoelectric constant or moderately reducing the sensor's natural frequency; while enhancing the resonant frequency requires optimizing the structural stiffness and mass distribution of the sensor.

3. Sensor Design Scheme

3.1 Sensor Material Selection

Piezoelectric materials include SiO_2, $BaTiO_3$, piezoelectric ceramics (PZT), and polyvinylidene fluoride (PVDF), among others. Accelerometers fabricated from PVDF piezoelectric film offer advantages such as excellent dynamic characteristics, broad frequency response range, high sensitivity, and superior flexibility. Therefore, PVDF piezoelectric film was selected as the piezoelectric material for the sensor in this study.

3.2 Sensor Structural Design

Piezoelectric accelerometers primarily adopt three structural configurations: shear type, flexural type, and compression type. Shear-type accelerometers feature a compact structure and small size, but suffer from complex manufacturing processes, higher costs, and limited maximum measurement range. Flexural-type accelerometers exhibit superior ultra-low frequency response performance; however, they possess lower resonant frequencies and poor impact resistance. Compression-type accelerometers offer a simple and robust structure, low manufacturing cost, high sensitivity, excellent signal-to-noise ratio, wide frequency response range, and the ability to withstand significant impact loads, making them suitable for high-frequency measurements[10].

During the turning process, the vibration amplitude generated by tool breakage or wear is significantly larger than under normal conditions. To accurately and comprehensively detect these vibration signals, a sensor with high sensitivity, a wide frequency response range, and high-frequency capability is essential. Consequently, the compression-type structure was selected. The designed sensor structure is illustrated in Figure 2.

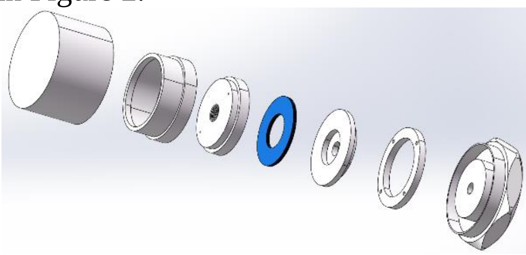


Fig.2 Overall structure of PVDF piezoelectric accelerometer

When the sensor is subjected to vibration, the proof mass exerts an inertial force proportional to the vibration acceleration on each PVDF piezoelectric film. Based on the direct piezoelectric effect, the PVDF piezoelectric films generate an electric charge proportional to the applied inertial force. Positive charges accumulate on the upper surface of the copper conductive sheets, while negative charges accumulate at the interface between the PVDF films and the base.

4. Finite Element Analysis

Based on the geometric model of the PVDF piezoelectric accelerometer, the sensor's geometric model was constructed using SOLIDWORKS software. This geometric model was then imported into ANSYS software to build the ANSYS finite element model of the sensor. The material property parameters for the PVDF piezoelectric film and the mechanical property parameters for the sensor component materials were input into the Engineering Data module, as detailed in Tables 1 and 2. The piezoelectric material (PVDF) and other structural materials of the sensor were meshed using SOLID226 and SOLID186 elements, respectively. The resulting mesh consisted of 327,561 elements and 598,010 nodes. The meshing result is presented in Figure 3.

As ANSYS software automatically detected the contacts within the imported model, boundary conditions were applied as follows: a fixed support constraint was applied to the bottom surface of the sensor, and a torque of 3040 $N \cdot mm$ was applied to the clamp ring. An acceleration load was subsequently applied to the entire sensor model. Through modal analysis and harmonic response analysis, the natural frequencies and operating frequency range of the sensor were determined[11].

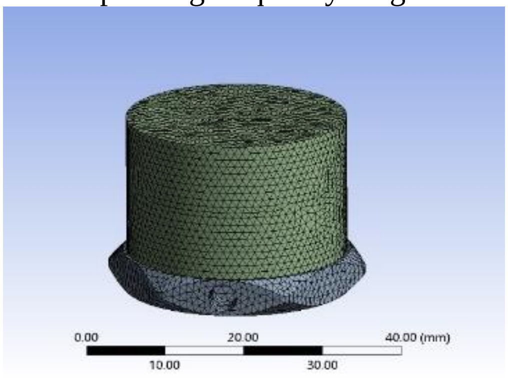


Fig.3 Finite element meshing result plot

Table 1 Performance parameters of PVDF piezoelectric films[12]

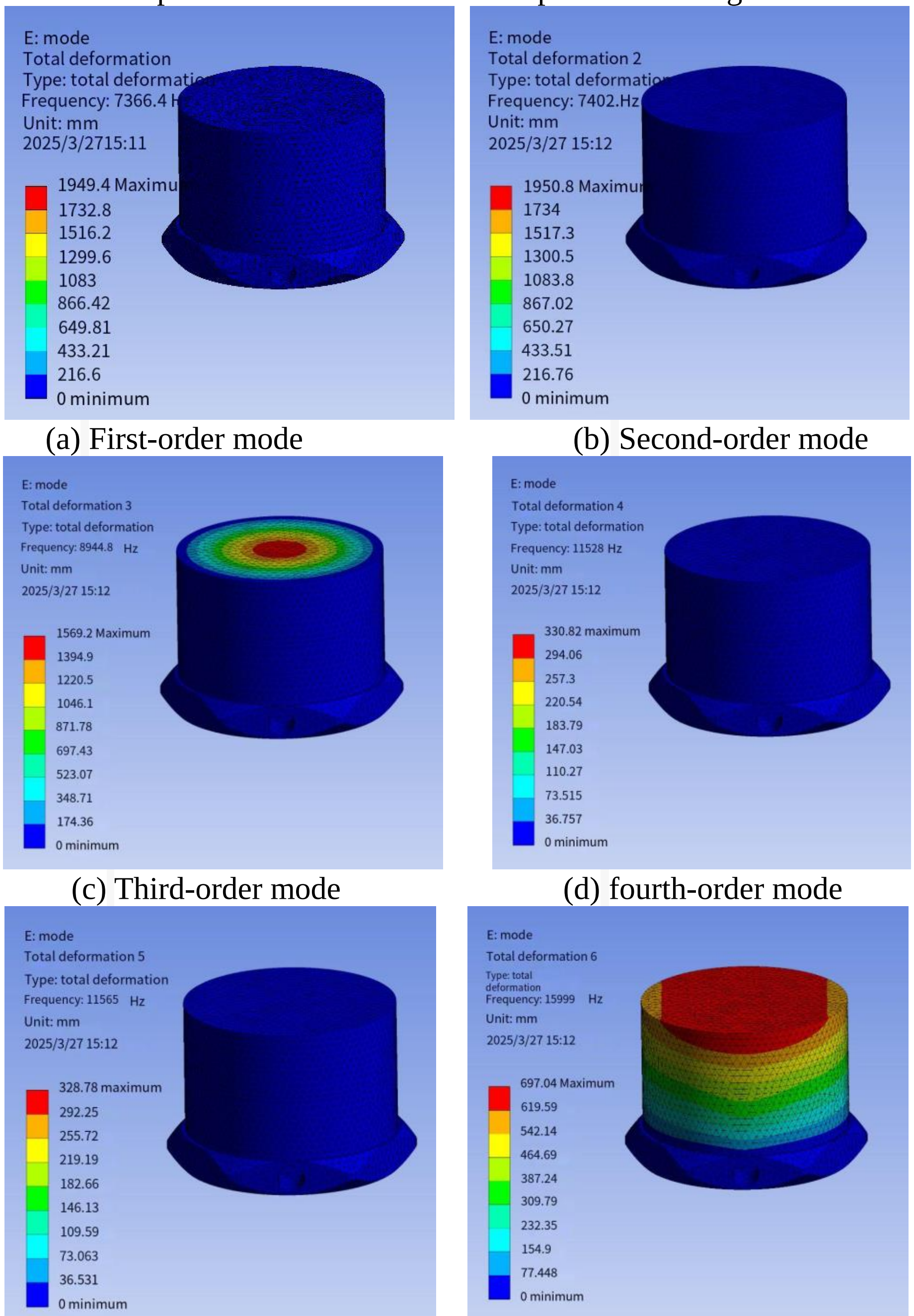
Performance Parameters	Numeric Value
Piezoelectric Strain Constant d_{31} (pC/N)	16~18
Piezoelectric Strain Constant d_{32} (pC/N)	5~6
Piezoelectric Strain Constant d_{33} (pC/N)	21
Piezoelectric Voltage Constant g_{33} (Vm/N)	0.2
Relative Dielectric Constant $\varepsilon/\varepsilon_0$	9.5±1.0
Electromechanical Coupling Coefficient K_{33}	10%~14%
Volume Resistivity $R(\Omega)$	≤3
Tensile Strength at Break σ_s (GPa)	0.035~0.05
Density ρ (g/cm^3)	1780
Poisson's Ratio μ	0.35
Elastic Modulus E (GPa)	2.4~2.6

Table 2 Sensor component materials and their mechanical properties

Component	Material	Young's modulus / GPa	Density /($g \cdot cm^{-3}$)	Poisson's ratio
Proof Mass	Structural Steel	200	7.85	0.3
Base	Structural Steel	200	7.85	0.3
Conductive Sheet	Brass	110	8.53	0.35
Insulating Sheet	General-purpose Plastic	1.5	0.91	0.42
Housing	Aluminum Alloy	70	2.70	0.33
Piezoelectric Material	PVDF	2	1.78	0.34
Clamp Ring	Stainless Steel	193	7.93	0.29

4.1 Modal Analysis

The upper cutoff frequency of the piezoelectric accelerometer is primarily constrained by its resonant frequency. The natural frequency, investigated as part of the static characteristics, is a critical parameter in structural design for withstanding dynamic loads. The vibration modes and natural frequency characteristics of the sensor were obtained using the modal analysis method within ANSYS software[13]. The mode shapes for the first six orders are presented in Figure 4.



(a) First-order mode (b) Second-order mode

(c) Third-order mode (d) fourth-order mode

(e) Fifth-order mode (f) Sixth-order mode

Fig.4 1st~6th order mode shape diagram

The natural frequencies corresponding to the first six mode shapes are 7366.4 Hz, 7402.0 Hz, 8944.8 Hz, 11528 Hz, 11565 Hz, and 15999 Hz, respectively.

4.2 Harmonic Response Analysis

The target vibration direction of the sensor is the z-axis direction. Harmonic response analysis was employed to solve the sensor's steady-state forced vibration. Based on the modal analysis results, boundary conditions were applied: a fixed support constraint was applied to the sensor base, and a torque was applied to the clamp ring section of the base. An inertial acceleration load was then applied along the z-axis direction. The first six natural frequencies identified from the modal analysis spanned a range of 0-15999 Hz. Since the maximum frequency from modal analysis is typically approximately 1.5 times the upper limit of the sweep range, the frequency range for harmonic analysis was defined from 0 to 10500 Hz. Within this range, 105 frequency points were specified, corresponding to a frequency step size of 100 Hz. For piezoelectric accelerometers, the damping ratio ζ typically ranges from 0.002 to 0.250. When $\zeta < 0.1$, the natural frequency is essentially consistent with the resonant frequency. Therefore, a damping ratio $\zeta = 0.02$ was adopted in this study. Under the excitation of the applied acceleration signal, the sensor undergoes harmonic motion. The harmonic response results for the entire sensor structure, obtained through the solution process, are presented in Figure 5.

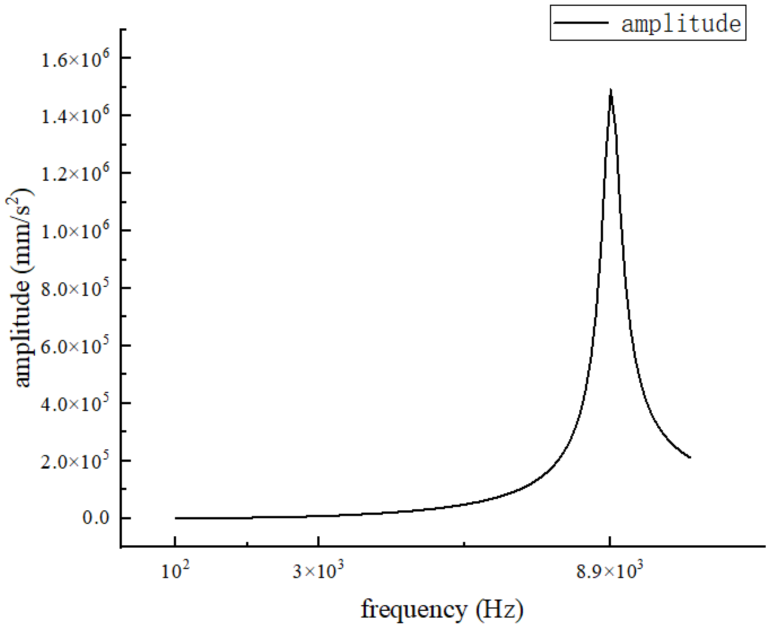


Fig.5 The overall harmonic response curve of the sensor

As shown in Figure 5, the average amplitude in the low-frequency region is approximately 2.09×10^3 mm/s². A distinct amplitude peak of 1.49×10^6 mm/s² occurs at 8900 Hz, indicating that the sensor resonates at this frequency, corresponding to a natural frequency of approximately 8900 Hz. Consequently, the third-order modal analysis result of 8944.8 Hz (shown in Figure 4) is confirmed as the sensor's fundamental natural frequency. According to the theoretical derivation in Section 2, the stable operating frequency range of the sensor is approximately one-third of its natural frequency. Combining this with the harmonic response analysis results in Figure 5, the stable operating frequency range is determined to be 100-3000 Hz. Within this frequency band, the frequency response curve is approximately linear, enabling stable monitoring of vibration signals. The simulation results validate the correctness of the theoretical analysis.

5. Sensor Calibration Experiment

To verify the correctness of the simulation results and calibrate the sensor's sensitivity, calibration tests were performed on the PVDF piezoelectric film accelerometer. During calibration, a vibration exciter (shaker) was used to provide controlled vibrational excitation. The output signal from the PVDF piezoelectric accelerometer was recorded using NI data acquisition software. The experimental setup for sensor calibration is illustrated in Figure 6.The sinusoidal excitation source for the shaker was generated by a signal generator. This digital signal was amplified by a power amplifier before being input to the shaker. The sensor transmitted the measured vibration signal to a charge amplifier, which converted the charge signal into a voltage signal and amplified it. An NI data acquisition card then transferred the amplified voltage signal to a host computer. Both the sensor under test (SUT) and a reference standard sensor were recorded simultaneously. The acquired data was saved to a designated storage system. Sensitivity test curves were generated using Origin software. The vibration sensor under test was calibrated using the standard piezoelectric vibration sensor as a reference, and its sensitivity was determined based on the test methodology.

Fig.6 Schematic diagram of the sensor calibration experimental test setup

The sensor under test and the standard sensor were mounted at the center of the shaker table using tesa™ specialty tape for measurement, as shown in Figure 7. Within the Vibration VIEW (calibration equipment adaptation software), an excitation signal of 160 Hz with accelerations ranging from 1 g to 20 g was set. Under these parameters, the charge sensitivity of the piezoelectric accelerometer was calibrated. The sensitivity curve was obtained by processing the data recorded by the NI acquisition software on the host computer using Origin software. The calibrated sensitivity of the PVDF piezoelectric accelerometer under test was determined to be 25.284 pC/(m·s^{-2}). The data acquisition and processing are depicted in Figures 8 and 9.

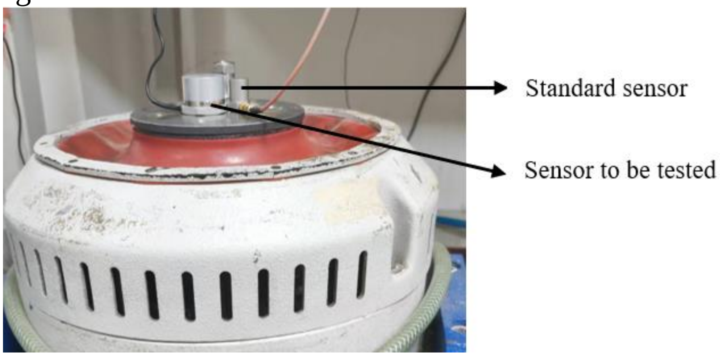


Fig.7 Sensor paste location map

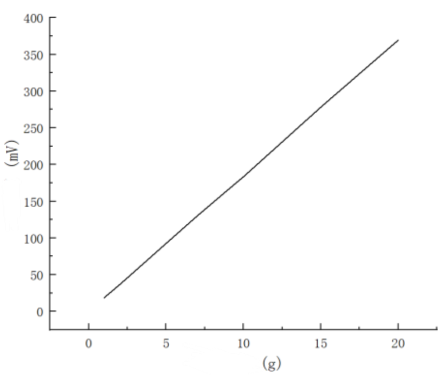


Fig.8 Standard sensor voltage vs. acceleration curve

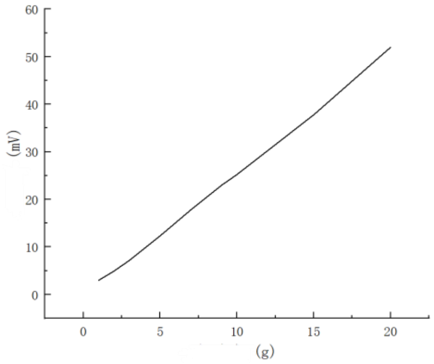


Fig.9 The voltage vs. acceleration curve of the sensor to be measured

Sweep frequency analysis of the piezoelectric accelerometer was performed under these parameter conditions (excitation signal: 0.5–4000 Hz, acceleration: 1–20 g). The frequency response curve was obtained by processing the data recorded by the NI acquisition software on the host computer using Origin software. The effective operational frequency range of the PVDF piezoelectric accelerometer under test was determined to be approximately 0.5 Hz to 2900 Hz. Minor deviations from the simulation results were observed, attributable to manufacturing tolerances; nevertheless, the experimental results demonstrate substantial agreement with the simulations. The data collection is shown in Figure 10.

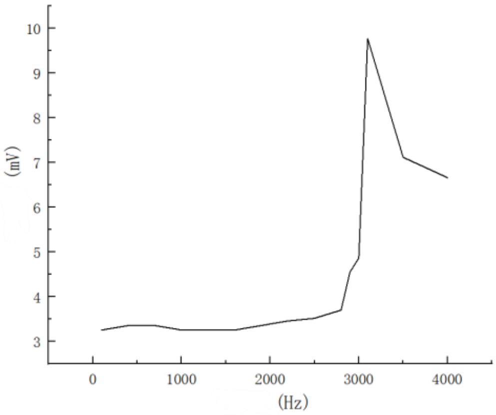


Fig.10 Swept frequency after origin processing

6. Turning Vibration Measurement Test

To validate the feasibility of the PVDF piezoelectric film accelerometer for detecting vibration signals, turning tests were conducted under different machining conditions. The sensor was mounted on the backside of the turning tool using a magnetic base, as shown in Figure 11.

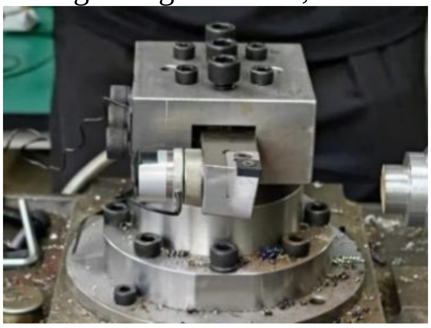
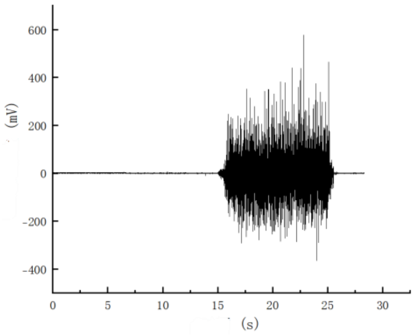


Fig.11 Schematic diagram of the sensor adsorption position

1) Influence of Cutting Depth on Vibration Signal

Tests were performed with a fixed spindle speed of 1100 rpm and a feed rate of 0.1 mm/r, using cutting depths of 0.4 mm and 0.8 mm. The acquired vibration signals are presented in Figures 12 and 13. The average voltage measured during the 0.4 mm depth cut was 102.37 mV, while it was 154.26 mV for the 0.8 mm depth cut. Increasing the cutting depth resulted in a significant increase in the amplitude of the vibration signal.



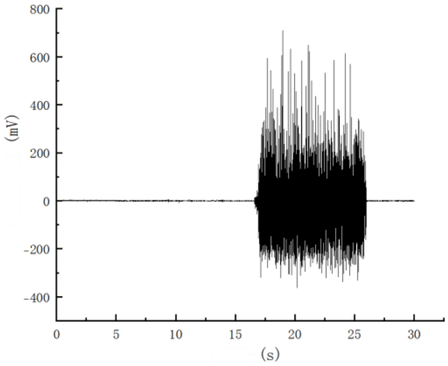
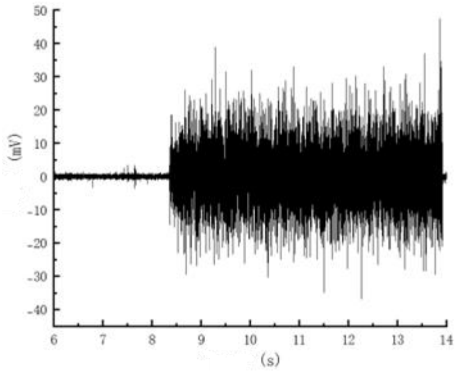


Fig.12 The feed is 0.1mm/r

Fig.13 The feed is 0.2mm/r

2) Influence of Feed Rate on Vibration Signal

Tests were performed with a fixed spindle speed of 500 rpm and a cutting depth of 0.8 mm, using feed rates of 0.1 mm/r and 0.2 mm/r. The acquired vibration signals are presented in Figures 14 and 15. The average voltage measured at the 0.1 mm/r feed rate was 11.64 mV, compared to 16.29 mV at the 0.2 mm/r feed rate. Increasing the feed rate increases the material removal per revolution and alters chip thickness, which also induces fluctuations in cutting forces. The sensor effectively resolved the changes in vibration energy corresponding to different feed rates.



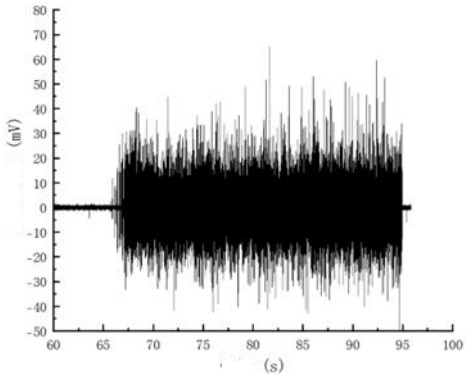


Fig.14 The feed is 0.1mm/r

Fig.15 The feed is 0.2mm/r

3) Influence of Spindle Speed on Vibration Signal

Tests were performed with a fixed feed rate of 0.2 mm/r and a cutting depth of 0.4 mm, using spindle speeds of 500 rpm and 1100 rpm. The acquired vibration signals are presented in Figures 16 and 17. The average voltage measured at 500 rpm was 10.37 mV, while it was 50.85 mV at 1100 rpm. The sensor accurately captured the differences in the system's harmonic response at varying spindle speeds, demonstrating its good frequency resolution and wide-band response characteristics.

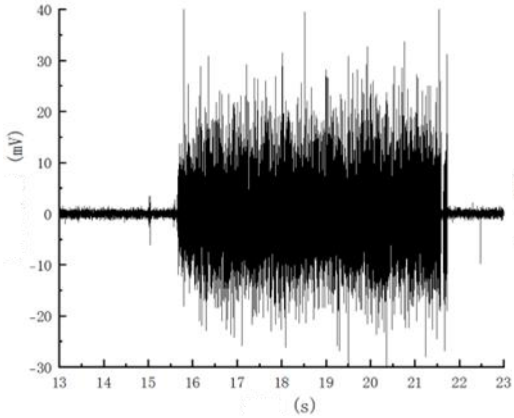


Fig.16 Spindle speed 500r

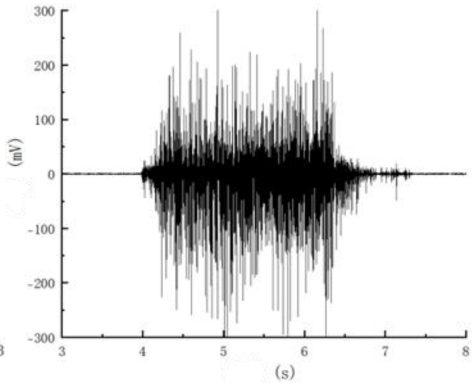


Fig.17 Spindle speed 1100r

From the comparative experiments described above, it is evident that the PVDF piezoelectric accelerometer yields distinct voltage signals under different turning parameters. It successfully detects and records changes in vibration state induced by variations in process parameters during turning. Therefore, the PVDF piezoelectric accelerometer with a vertical compression structure proves to be a viable tool for monitoring vibration signals during turning operations, providing reliable data for subsequent research on tool wear detection in machining processes.

7. Conclusion

To address the limitations of existing sensors used for monitoring vibration signals in turning operations-namely low sensitivity, narrow frequency range, and complex structures-a novel PVDF piezoelectric film accelerometer was designed.

1) The mechanical model of the sensor was established. It was determined that employing a vertical compression structure design and optimizing the material of the sensitive element would enhance both the sensor's natural frequency and sensitivity.

2) The sensor structure was designed, the piezoelectric material and other component materials were selected, and the finite element model of the sensor was constructed to analyze its performance. Simulation results indicated a natural frequency of 8944.8 Hz and an operational frequency range of 100-3000 Hz, meeting the requirements for vibration signal detection.

3) The designed sensor underwent calibration and practical application testing. The experimental results confirmed an effective operational frequency range of 0.5-2900 Hz and a sensitivity of 25.284 pC/(m·s^{-2}). These characteristics satisfy the requirements for vibration signal detection concerning both frequency bandwidth and high sensitivity.

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References

[1] Huang Yi Jin. Research on PVDF-based seismic geophone[D].Kunming University of Science and Technology, 2011.
[2] Klaas Hauke Baumgärtel, DanielZöllner, Karl-LudwigKrieger. Classification and Simulation Method for Piezoelectric PVDF Sensors[J]. Procedia Technology, 2016, 26: 491-498.
[3] Nguyen V, Melkote S, Deshamudre A, et al. PVDF Sensor Based Monitoring of Single-Point Cutting[J]. Journal of Manufacturing Processes, 2016, 24: 328-337.

[4] Yan Ming. Research on health monitoring of high-voltage transmission tower based on PVDF piezoelectric sensor[D].Kunming University of Science and Technology, 2017.

[5] Mao Shi Jie, Lei Ti Gao, Wang Yan Shan, et al. Research on the design and testing technology of a planar shear piezoelectric acceleration sensor[J].Science and Technology Innovation and Application,2018,(33):28-30 32.

[6] Lu Min, Hu Hongbo, Zhu Gang, et al. Trigonometric Shear Piezoelectric Accelerometer Resistant to Severe Environment [J]. Measurement and Control Technology, 2018, 37: 109-111.

[7] L. Wei, L. Yu, J. Wang, D. Jiang, Q. Liu and Z. Liu, "An FBG-Sensing Two-Dimensional Vibration Sensor Based on Multi-Axis Flexure Hinge," in IEEE Sensors Journal, vol.19, no. 10, pp. 3698-3710, 15 May15, 2019,DOI: 10.1109/JSEN.2019.2895232.

[8] Jiang Shuai Shuai, Shi Yan nan, Zhang Chong Chong, et al. Design of piezoelectric acceleration sensor for triangular shear micro seismic monitoring[J].Piezoelectricity and Acousto-Optic,2021,43(06):857-862.

[9] ZHU Xu. Design and Analysis of Electromagnetic MEMS Vibration Sensor[D].North University of China,2024.

[10] Wu T, You D, Gao H, et al. Research Status and Development Trend of Piezoelectric Accelerometer[J]. Crystals, 2023,13(9):

[11] Xu Xing Sheng, Li Ying Jun, Wang Gui Cong, et al. Design of piezoelectric six-dimensional force sensor with spoke structure[J].Optical Precision Engineering,2020,28(12):2655-2664.

[12] Hong ping Hu, Chun Zhao, Sheng yuan Feng, et al. Adjusting the resonant frequency of a PVDF bimorph power harvester through a corrugation-shaped harvesting structure[J]. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2008, 55(3):668-674.

[13] Sheikhaleh A, Abedi K, Jafari K.A Proposal for an Optical MEMS Accelerometer Relied on Wavelength Modulation With One Dimensional Photonic Crystal[J].Journal of LightwaveTechnology,2016,34(22):5244-5249.