

Acoustic Emission Valve Disc Slight Opening Recognition Technology

Wenhao Hu^{1, a}, Long Chen^{1, b}, Xiang Shi^{1, c}, and Qingyuan Huang^{1, 2, d}

¹ School of Automation and Information Engineering, Sichuan University of Science and Engineering, Zigong 643000, China

² Artificial Intelligence Key Laboratory of Sichuan Province, Zigong 643000, China

^a321085404304@stu.suse.edu.cn, ^b321085404308@stu.suse.edu.cn

^c322085404205@stu.suse.edu.cn, ^dqyhuang@suse.edu.cn

Abstract

Currently, there is no universally recognized valve disc slight opening identification technology for online verification in safety valves. For spring-loaded safety valves, there is no online verification method available when the mid-range value is unknown. Particularly in the online verification of spring-loaded safety valves, the existing methods generally suffer from the drawback of poor verification accuracy. This paper proposes a novel approach, centered around a computer system, comprising an acoustic emission sensor, a signal amplifier, a valve stem lifting device, and an additional acoustic emission sensor. The signals indicating the slight opening of the safety valve disc are collected by the acoustic emission sensors, and the extracted features of these signals are subsequently analyzed for identification purposes. This method exhibits high accuracy and generalizability, thereby enhancing the accuracy of online verification results for safety valve disc slight opening. The experimental setup complies with the "TSG-ZF001-2006" (Regulations for Safety Technical Supervision of Safety Valves), and the experimental apparatus demonstrates an error rate below 2% compared to the offline calibration bench, outperforming other methods with 5%-10% higher accuracy than safety valve online verification devices. This approach holds significant potential for widespread adoption within the industry, aligning with SCI (Science Citation Index) standards.

Keywords

Safety Valve; Sensor; In Your Paper; Acoustic Emission; VMD.

1. Introduction

Safety valves are widely used as overpressure protection devices in the power, petrochemical, and other industries involving pressurized equipment, serving as a safeguard for the secure operation of systems. Currently, the calibration of safety valves primarily falls into two categories: offline calibration and online calibration. According to the regulations outlined in "TSG-ZF001-2006" (Safety Valve Safety Technical Supervision Rules), safety valves must undergo at least one calibration annually. Offline calibration entails shutting down the production unit, disassembling the safety valve for calibration, resulting in significant resource wastage throughout the entire process. However, the advent of online calibration technology for safety valves allows calibration to be conducted on-site, enabling uninterrupted production without the need for shutdowns, thus simplifying and expediting the calibration process, leading to substantial resource savings[1]. Consequently, online calibration technology for safety valves has gained widespread acceptance and usage in the industry.

In addition, a specific category of safety valves installed on pipeline containers without isolation valves faces constraints regarding disassembly for calibration, necessitating exclusive reliance on online calibration methods.

The operational principle of safety valves is grounded in the equilibrium of forces, specifically the spring balance principle, and the response to pressure exceeding the preset value. Spring-loaded safety valves incorporate an adjustable pressure-setting spring, the preload force of which can be tailored according to system design requirements to determine the preset pressure threshold. During normal operation, the spring's preload force is in equilibrium with the system pressure, maintaining the valve disc in a closed state, preventing fluid flow through the valve. When the system pressure reaches or exceeds the preset pressure threshold, the excess pressure overcomes the spring's preload force, initiating spring compression and generating an imbalanced force, causing the valve disc to start opening. Once the spring is subjected to sufficient pressure, the valve disc is pushed open, creating a pathway for fluid release from the safety valve.

As the pressure decreases to the designated safety range, the preload force of the spring surpasses the force of the pressure, restoring the equilibrium state. This results in the closure of the valve disc, halting the fluid flow from the safety valve[2]. The operational principle of spring-loaded safety valves can be fine-tuned by adjusting the preload spring force to achieve different pressure setting ranges. This type of safety valve finds applications in various scenarios such as pressure vessels, boilers, pipeline systems, safeguarding systems against damage from excessive pressure. Through meticulous design and adjustment, spring-loaded safety valves can reliably operate, ensuring that systems function within the designated safety operational range..

2. On-line Calibration Technology of Safety Valves

2.1. Disc Micro-motion Recognition Technology

In the online verification of safety valves, accurately determining whether the safety valve is open is a key technology and challenge that directly affects the accuracy and effectiveness of the online verification. Currently, the commonly used method in safety valve online verification involves placing a displacement sensor to detect the displacement of the valve stem during lifting. When the displacement reaches a certain threshold, it is judged that the valve is open. However, this method assumes that the displacement sensor is absolutely perpendicular to the valve stem. Due to the deformation of mechanical devices under additional force, the displacement sensor may become non-vertical, leading to imprecise measurements. Additionally, the deformation of mechanical fixtures varies for different valves.

To address these issues, Ding Weicheng, Chen Haofeng, and others proposed the Spring Deformation Pressure-Force Curve Method in the paper titled "Micro-Opening Identification Technology for Spring Safety Valve Online Verification" [3]. This method primarily utilizes the deformation pressure-force curve of the spring for micro-opening identification. In practical systems, when additional force is applied to the valve stem, the mechanical device undergoes deformation, which is detected by a rod-type displacement sensor. The micro-opening of the valve inevitably causes displacement of the valve stem, which is detected by the displacement sensor.

Therefore, the micro-opening of the valve occurs precisely at the moment when the displacement sensor undergoes displacement. Combining the theoretical foundation of the inflection point identification method for additional force curves, the displacement change of the displacement sensor is used as the trigger signal for initiating the measurement of additional force. Consequently, the slope of the spring deformation pressure-force curve before micro-opening is significantly higher than the slope after micro-opening. The advantage of

using the spring deformation pressure-force curve method is that a displacement sensor generates displacement as the trigger signal for the pressure sensor without the need for uniformly applied additional force, resulting in accurate micro-opening identification.

The aforementioned methods measure whether the safety valve is open indirectly by measuring the lifting force, pre-tension force of the spring, and displacement value of the valve stem. They do not directly receive the signal emitted by the safety valve when it is micro-opened. When a safety valve opens, it emits an audio signal. Therefore, audio methods can be used to identify the micro-opening of safety valves. When the valve opens, airflow noise can be detected by a sound pickup probe and identified through audio amplification. However, this method is highly susceptible to noise, and the determination is mainly subjective, relying on verification personnel to judge whether the safety valve is open through earphones, leading to a significant reduction in detection accuracy. In recent years, an increasing number of people have applied non-destructive testing technology to safety valve inspection. Acoustic emission, as a mature non-destructive testing technology, has also been applied in safety valve-related applications.

2.2. Acoustic Emission Micro-Opening Identification Technology

Acoustic Emission Micro-Opening Identification Technology:

This paper proposes a novel method based on acoustic emission technology for determining the micro-opening status of a safety valve. When the valve disc of the safety valve is in a micro-open state, the medium will be ejected between the valve seat and the valve disc, generating stress waves and initiating the phenomenon of acoustic emission. Therefore, by collecting and recording the acoustic emission signal changes before, during, and after the micro-opening of the valve disc using an acoustic emission sensor, in combination with lift force data recorded by a pressure sensor and the theoretical basis of additional force recognition, the acoustic emission signal during valve disc micro-opening is used as a trigger signal to initiate the measurement of additional force. With this method, accurate determination of the micro-opening status of the safety valve can be achieved, and the accurate set pressure for opening can be identified. The advantage of this method lies in directly obtaining the signal of the safety valve disc micro-opening, avoiding the problem of misjudgment caused by displacement sensor displacement, and enabling safety valve calibration to be completed without knowledge of the internal diameter of the safety valve.

Acoustic Emission Signal Processing Method:

The acoustic emission signal includes multiple parameters such as amplitude, MARSE, delay, count, and rise time, which can be measured as part of the explanation of the acoustic emission phenomenon. At the moment of the safety valve disc micro-opening, the signal of the safety valve micro-opening belongs to a burst-type acoustic emission phenomenon. In continuous acoustic emission signals, most burst-type acoustic emission phenomena can be detected on a millisecond scale. The signal strength of burst-type events undergoes instantaneous changes, causing variations in amplitude. These acoustic emission signals are simultaneously released from the valve disc and mixed with environmental noise, making it exceptionally difficult to accurately distinguish their operational status. Therefore, to adapt to the level of noise, more advanced processing methods are required to separate these signals.

In this study, we defined transient events based on burst-type acoustic emission signals at the moment of safety valve disc micro-opening. To extract signal features related to the acoustic emission signal of valve disc micro-opening from higher noise, we employed Variational Mode Decomposition (VMD) and autoencoders to automatically distinguish the valve disc micro-opening signal from other signals, reducing dependence on subjective judgments. This method not only improves the accuracy of online calibration of safety valves but also provides a new and feasible solution for practical applications.

Over the past few decades, with the rapid development of signal processing techniques and machine learning, significant progress has been witnessed in these fields, allowing computers to more accurately identify and analyze complex signals. Particularly in situations where environmental noise is substantial, and the frequency of acoustic emission data is high, the problem becomes more complicated because different frequencies may lead to modal overlap and the occurrence of false components, posing significant challenges to signal interpretation and diagnosis.

The primary method for analyzing sensor data is usually Empirical Mode Decomposition (EMD). However, EMD may be limited in performance when facing issues such as modal overlap and false components. This is one of the reasons why we chose to use Variational Mode Decomposition (VMD), as it possesses unique advantages in these aspects.

Through VMD, we can more clearly separate signal components at different frequencies, helping to highlight the characteristics of valve disc micro-opening more distinctly for accurate feature extraction, even in the absence of internal medium or trace amounts of medium. Additionally, VMD has inherent adaptability, meaning it can automatically adjust the decomposition process based on the characteristics of the input signal, accommodating the existence of different frequency components and potential noise interference. In the case of acoustic emission signals during valve disc micro-opening, environmental noise and interference are often present, making signal processing more complex. However, it is the adaptability of VMD that enables effective handling of these challenges, extracting key signal components, thereby improving signal resolution and accuracy.

Furthermore, VMD provides researchers with the ability to selectively extract signal components within a specific frequency range, which is beneficial for the localization and fault diagnosis of valve disc micro-opening. By selecting a specific frequency range, we can focus on key vibration modes, gaining a more comprehensive understanding of the characteristics and behavior of valve disc micro-opening.

Numerous research findings indicate that signal processing techniques and statistical machine learning methods have achieved good results in the field of state recognition based on acoustic emission signals. Researchers at Kunming University of Science and Technology, such as Yu Rui et al., used EMD to process acoustic emission signals and obtained several Intrinsic Mode Functions (IMFs). Each IMF was subjected to AR modeling to extract feature vectors, and experiments showed that SVM could accurately identify different acoustic emission signals. Researchers at East China University of Electric Power, including Li Dazhong et al., used Empirical Mode Decomposition (EMD) to process ultrasonic defect signals to obtain feature vectors. They used a genetic algorithm to optimize the support vector machine model, and experimental results showed that the genetic algorithm could effectively improve the performance of the support vector machine. Researchers at Beijing University of Chemical Technology, led by Jiang Zhinong, applied the VMD algorithm to decompose cylinder head vibration signals, reconstructed IMF components to obtain feature matrices, and then calculated the singular value sequence of the feature matrices. They used a random forest classifier to classify this sequence, and the study found that this method had a higher recognition rate under diesel engine variable working conditions.

Therefore, the choice of using VMD as the method for processing acoustic emission signals in this paper is well-considered. It possesses unique advantages in handling high-frequency, complex signals, modal overlap, false components, and other challenges, providing a powerful tool and method for the recognition and analysis of valve disc micro-opening. This choice will contribute to improving recognition accuracy.

The specific process of VMD decomposition can be understood as finding the optimal solution to a variational problem, which can be correspondingly transformed into the construction and solution of a variational problem.

2.2.1. VMD

The specific process of Variational Mode Decomposition (VMD) can be understood as the optimal solution to a variational problem, which can be correspondingly formulated and solved.

1) Assume that the multi-component signal is composed of K analysis signals of finite bandwidth modal components, denoted as $v_K(t)$ is modulated to the corresponding baseband:

$$[(\delta(t) + \frac{j}{\pi t}) * v_K(t)]e^{-j\omega_k t} \tag{1}$$

2) Compute the square norm L^2 of the demodulation gradient and estimate the bandwidth of each modal component, as presented by the following formula.

$$\begin{cases} \min_{v_k, \omega_k} \sum_k \left\| \partial_t \left[(\delta(t) + \frac{j}{\pi t}) * v_K(t) \right] e^{-j\omega_k t} \right\|^2 \\ s. t. \quad \sum_k V_K = s \end{cases} \tag{2}$$

In the above equation, $\{v_K\}=\{v_1, \dots, v_K\}$ represents the decomposed Intrinsic Mode Function (IMF) components, and $\{\omega_K\}=\{\omega_1, \dots, \omega_K\}$ represents the central frequencies of the respective components.

To find the optimal solution for the constrained variational problem, we first introduce the Lagrange multiplier $\tau(t)$ and the second-order penalty factor α . This transforms the constrained variational problem into an unconstrained variational problem. The second-order penalty factor α ensures the accuracy of signal reconstruction in a Gaussian noise environment. The Lagrange multiplier $\tau(t)$ ensures the strictness of maintaining the constraint conditions. The extended Lagrangian expression is as follows:

$$L(\{v_k\}, \{\omega_k\}, \tau) := \alpha \sum_k \left\| \partial_t \left[(\delta(t) + \frac{j}{\pi t}) * v_K(t) \right] e^{-j\omega_k t} \right\|^2 + \|s(t) - \sum_k v_k(t)\|^2 + (\tau(t), s(t) - \sum_k v_k(t)) \tag{3}$$

3) Then, the alternating direction method of multipliers (ADMM) is utilized to iteratively update each component and central frequency. This eventually leads to the saddle point of the unconstrained model, which is the optimal solution to the original problem. All components can be obtained in the frequency domain according to the following expression:

$$v_k^{\wedge n+1}(\omega) = \frac{s^{\wedge}(\omega) - \sum_{i \neq k} v_i^{\wedge}(\omega) + \tau^{\wedge}(\omega)/2}{1 + 2\alpha(\omega - \omega_k)^2} \tag{4}$$

In the above equation, ω represents the frequency, $v_k^{\wedge n+1}(\omega)$, $s^{\wedge}(\omega)$, $\tau^{\wedge}(\omega)$ correspond to the Fourier transforms of $v_k^n(t)$, $s(t)$, $\tau(t)$ respectively.

4) $v_k^{\wedge n+1}(\omega)$ is the residual after Wiener filtering of $s^{\wedge}(\omega) - \sum_{i \neq k} v_i^{\wedge}(\omega)$, and the algorithm re-estimates the centroid frequency based on the power spectrum centroid of each component. The specific process is as follows:

Initialize $\{v_k^{\wedge 1}\}, \{\omega_k^{\wedge 1}\}, \{\tau_k^{\wedge 1}\}$ and n.

Execute the cycle: $n=n+1$.

When $\omega > 0$, update ω_k^{\wedge} according to the formula ().

Update ω_k :

$$\omega_k^{n+1} = \frac{\int_0^{\infty} \omega |v_k^{n+1}(\omega)|^2 d\omega}{\int_0^{\infty} |v_k^{n+1}(\omega)|^2 d\omega}$$

5) Updating τ^{\wedge}

$$\tau^{\wedge n+1}(\omega) = \tau^{\wedge n}(\omega) + \tau(s^{\wedge}(\omega) - \sum_k v_k^{\wedge n+1}(\omega))$$

6) Repeat steps (2) to (5) until the iteration stopping condition is satisfied:

$$\sum_k \left\| v_k^{\wedge n+1} - v_k^{\wedge n} \right\|_2^2 / \left\| v_k^{\wedge n} \right\|_2^2 < \varepsilon$$

3. Research Methods

References are cited in the text just by square brackets [1]. (If square brackets are not available, slashes may be used instead, e.g. /2/.)

3.1. Two Or more

Simulation experiments mainly consist of a safety valve simulation working environment and an acoustic emission acquisition system. The experimental setup includes a horizontal air tank, a stop valve, a gas pressure gauge, a gas control valve, a pressure gauge, a nitrogen cylinder, a pressure control valve, hoses, a spring-loaded safety valve, an acoustic emission acquisition system, a vent valve, and a safety valve offline calibration stand.

The selected safety valve is manufactured by Beijing Aerospace, with a nominal inlet pressure of 600 pounds for the spring-loaded safety valve. To simulate actual working conditions, a small amount of pressure is set inside the pressure vessel.

The acoustic emission acquisition system uses the acoustic emission detection system produced by Changsha Xiangpeng Electronic Technology Co., Ltd. It includes an acoustic emission sensor, low-noise cables, a preamplifier, coaxial cables, an acoustic emission acquisition card, and a PC. According to the "TSG-ZF001-2006" (Safety Valve Safety Technical Supervision Regulations), the structure of the acoustic emission detection system includes a lifting device and a signal acquisition system. The mechanical lifting device is fixed on the top of the safety valve and consists of a mechanical frame, a hydraulic jack, and a connecting rod that connects to the valve stem. The hydraulic pump is used to apply lifting force, drive the valve stem upward, balance the pre-tension force of the spring, and manually achieve the opening condition of the safety valve.

The signal acquisition system consists of an acoustic emission sensor, a data acquisition card, and a computer. This system is used to collect the acoustic emission signals when the valve disc micro-opens. In addition, a pressure sensor is installed above the hydraulic jack to monitor the lifting force applied by the hydraulic cylinder, thereby real-time monitoring the lifting force ΔF of the safety valve.

The safety valve offline calibration stand uses equipment from Chengdu Sti-O Technology Co., Ltd. It is equipped with 0.4-level precision test pressure gauges and pressure transmitters with accuracies of 1.6 MPa, 4 MPa, 10 MPa, 25 MPa, and 60 MPa, as well as a 25 MPa gas pressure

gauge. The control panel has 4 channel valves, calibration valves, and pressure relief valves, and the control console is equipped with a gas-driven hydraulic pump. The clamping table is equipped with a test base and a set of fixed fixtures. The medium clamping table is suitable for testing safety valves with diameters ranging from DN15 to DN200, while the large clamping table is suitable for testing DN250 to DN500 safety valves. The accuracy of this offline calibration system fully complies with the relevant regulations of TSG ZF001-2006 "Safety Valve Safety Technical Supervision Regulations."

To better simulate the environment in actual work, during acoustic emission detection, the safety valve needs to be in a hot state (working state), which means there must be a trace amount of pressure below the safety valve. Using the lifting device achieves micro-opening of the valve disc under trace amounts of gas. First, install the safety valve on the experimental apparatus, connect it to the safety valve acoustic emission detection system; then, turn on the gas source, adjust the pressure inside the air tank to reach the pressure required for online calibration of the safety valve.

3.2. Feature Recognition of Safety Valve Disc Micro-opening Signals

In the process of valve disc micro-opening signal feature recognition, we selected different types of safety valves and conducted simulated experiments at different set pressures to collect time-frequency domain signals during valve disc micro-opening. These signals were extensively analyzed, and the obtained results were compared with the set pressure values obtained from the offline calibration bench of the safety valve.

In the analysis of the raw signals, the choice of VMD decomposition parameters was based on a profound understanding of signal characteristics and the practical requirements for decomposition results. Specifically, setting $\alpha=300,000$ aimed to effectively capture the low-frequency information of the signal, while $\tau=0$ indicated that each modal function has the same time scale to ensure similar temporal characteristics. Choosing $K=6$ was based on prior knowledge of signal frequency and structure to avoid information loss while maintaining lower computational complexity. The setting $DC=0$ removed the DC component, concentrating the decomposition results on the varying part of the signal. The choice of $init=1$ used a uniform distribution of random numbers for initialization, introducing some randomness. Finally, $tol=1e-7$ was chosen to achieve high precision while maintaining computational efficiency.

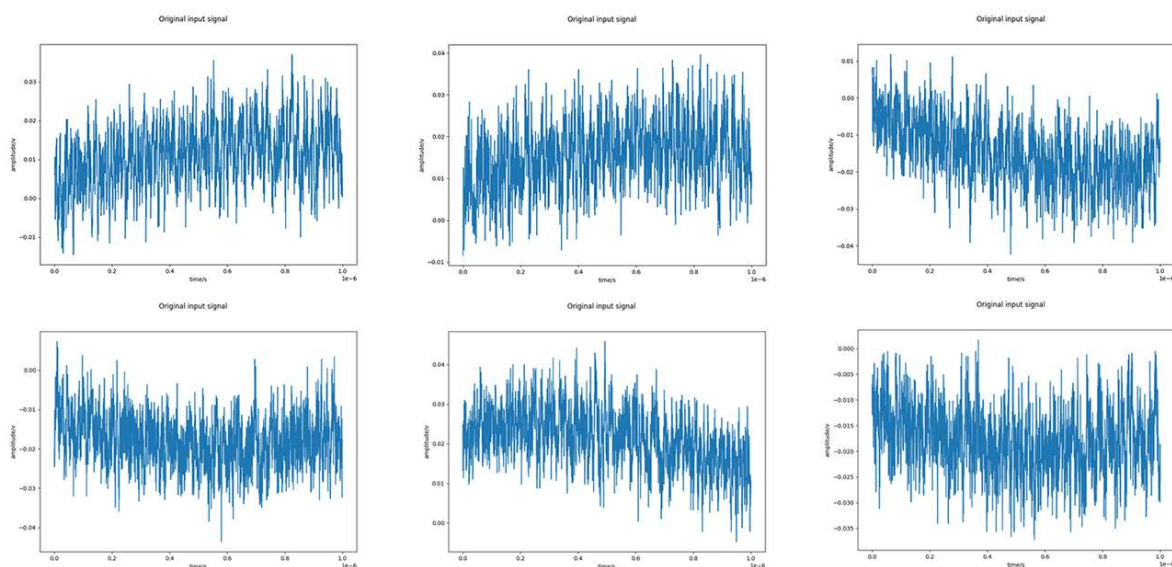


Figure 1. ove shows the collected original acoustic emission signal, which contains a considerable amount of ambient noise.

These parameter choices were made to ensure that the VMD decomposition performs optimally for the task at hand.

Through the analysis of the actual situation of safety valves, the proposed VMD method has been validated as effective and feasible.

In dealing with the signals of safety valve valve micro-opening and background noise, which cannot be clearly distinguished in the time domain, VMD decomposes these signals into several modal components with different central frequencies, allowing us to compare these signals at different scales. As shown in the figure, from the original signal, the 6th modal component (IMF6) clearly identifies the point of valve micro-opening. It can be seen that the signal features of valve micro-opening have been successfully extracted.

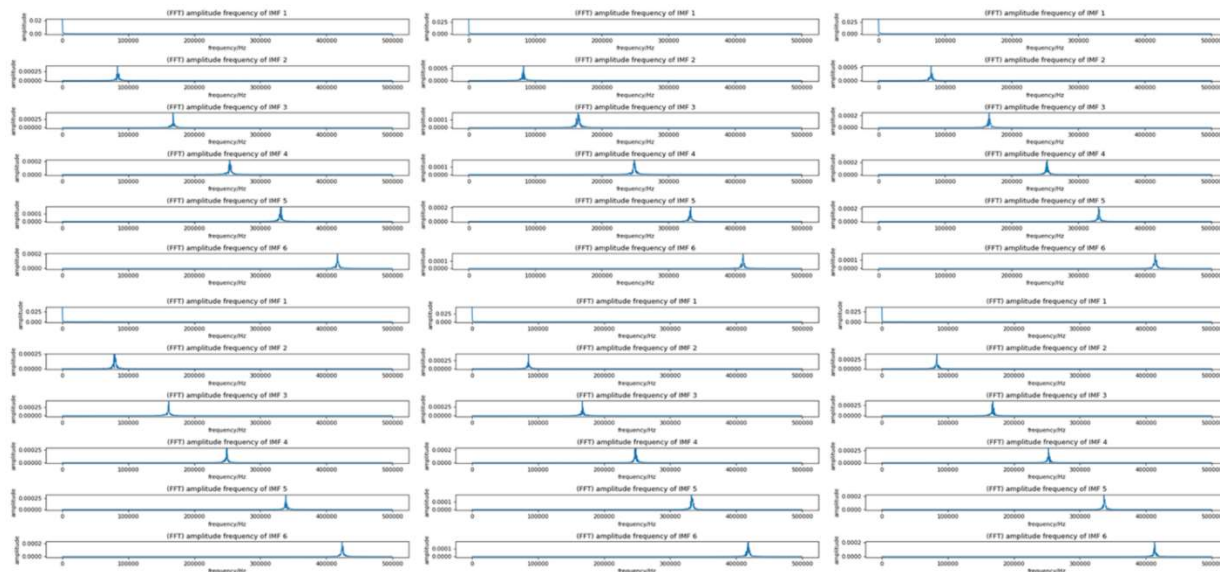


Figure 2. IMF component spectrum

"Comparing the measured values at various pressure levels with the experimental data from the offline verification platform, as shown in Table 1. It can be observed that the acoustic emission micro-start recognition technology accurately.

Table 1. Acoustic emission method

Offline verification	Acoustic emission method	Traditional online verification	Percentage Error Values
0.25Mpa	0.25Mpa	0.26Mpa	0%
0.50Mpa	0.50Mpa	0.50Mpa	0%
0.75Mpa	0.75Mpa	0.75Mpa	0%
1.00Mpa	1.00Mpa	1.05Mpa	0%
1.25Mpa	1.25Mpa	1.30Mpa	0%
2.80Mpa	2.85Mpa	3.00Mpa	2%

4. Conclusion of the Experiment

The regular inspection of safety valves is a crucial measure to ensure the accurate and reliable operation of safety valves and eliminate safety hazards in protected pressure equipment. The valve disc micro-opening identification method based on acoustic emission can accurately identify the safety valve online inspection instrument, which is designed as a key technology,

with small errors and high inspection accuracy. It is particularly suitable for complex environments with high noise levels, such as the petrochemical industry. Therefore, its widespread application can achieve significant economic and social benefits.

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