Ventilation Pipeline Safety Early Warning System Based on Pipe Wall Vibration and Sound Wave

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Abstract: Due to the limitation of working conditions and working environment, the ventilation pipeline safety monitoring system in an underground laboratory is facing the technical difficulties of high wind speed and high background noise. In order to effectively guarantee the safe operation of fresh air system, an abnormal early warning method for pipeline operation based on pipe wall vibration and acoustic wave is proposed, which can realize the monitoring and location of pipeline resonance and other safety incidents.

1. Introduction

The radioactivity of the inert gas radon will cause background interference to the low background and high purity germanium γ spectrum measurement device, as well as the detection experiments of rare events such as dark matter, neutrino free double β decay and neutrino, which will limit the improvement of experimental sensitivity[1]. Fresh air and supporting system are important links in the infrastructure construction of underground laboratory. Some related subjects have been tested and studied that the radon concentration in the air of an underground hall is $\left(10^{1\pm1}\right)Bq \cdot m^{-3}$ and $\left(86\pm25\right)Bq \cdot m^{-3}$ before and after the completion of the ventilation facilities. When the maintenance of the ventilation facilities are completed and operated normally, the radon concentration in the air can be maintained at $\left(30\sim 40\right)Bq \cdot m^{-3}$. In order to further reduce the interference of radon background radiation, the fresh air and supporting system of the underground laboratory use nitrogen with very low radon concentration to wash the inner cavity of the shield. So safety monitoring and positioning become the key to ensure the normal operation of the fresh air system pipeline.

2. Current Situation of Ventilation Pipeline Safety Early Warning Technologies

After long-term development, various pipeline safety technologies have been developed at home and abroad, effectively ensuring the safe operation of the pipeline. Common pipeline safety technologies include: pipeline safety monitoring system, pipeline safety early warning system, pipeline detection and integrity management system, etc. Pipeline safety early warning system includes distributed optical fiber, acoustic and other technologies, which are used for early warning of external damage of communication optical cable, oil, gas and water pipelines. The high-sensitivity sensor installed outside the pipeline can monitor the signal that may threaten the pipeline safety. Before the criminals destroy the pipeline or the construction accidents happen, the behaviors can be forewarned and positioned, so as to achieve the purpose of prevention in advance.
2.1 Distributed Optical Fiber Pipeline Security Early Warning

Based on the principle of optical fiber sensing technology, the pipeline optical fiber early warning and monitoring system (OFSEW) uses the buried optical cable as the vibration sensor. When there are events such as human activities and mechanical operation around the sensing optical cable, the vibration signal generated will cause strain of the optical cable, change the phase and polarization state of the optical cable, and transmit it to the early warning system through the optical fiber sensing system. Data acquisition and processing terminal, the acquisition terminal converts analog signal into digital signal, judges and locates the vibration signal, and transmits it to the early warning monitoring terminal through the network to realize the alarm of sound and interface, and precisely locates the vibration location. At the same time, the system has the advantages of high positioning accuracy of OTDR and good detection sensitivity of optical interference technology. Compared with the traditional negative pressure wave method and sound wave method, it has the advantage of pre-warning. It can monitor the dangerous operation and pipeline leakage on the ground in real time, and alarm and locate when the pipeline is threatened.

2.2 Acoustic Pipeline Security Early Warning

The sound wave early warning system of the pipe wall is to realize the safety early warning of the pipe by monitoring the sound wave signal along the pipe body with the high sensitivity sensor installed on the outer wall of the pipe. Before the criminals destroy the pipeline, the criminal behavior can be forewarned and positioned, which can achieve the purpose of prevention in advance. Its working principle is: when the pipe body is damaged, the on-site monitoring terminal carries out comprehensive calculation and analysis on the acoustic signal of the pipe wall monitored. When it is determined that the pipe is threatened, it will transmit the signal characteristics of the threat event to the monitoring center through the wireless communication network, and the monitoring center uses the intelligent analysis methods such as time-frequency joint analysis and neural network expert system for secondary judgment. Different event types are classified and located.

3. Technical Route of Ventilation Pipeline Monitoring System

Due to the limitation of working principle and environment, the working condition of ventilation pipeline is quite different from that of long-distance pipeline, so its safety monitoring faces great technical challenges: (1) low pressure, large pipe diameter, low signal intensity of leakage and other faults; (2) high wind speed, large background noise; (3) intermittent operation, resulting in great interference sound signal; (4) the gas medium (air or nitrogen) has a large elasticity, under the same amplitude, low signal energy and short transmission distance makes the leakage detection difficult.

In order to solve the above technical problems, an early warning method based on pipe wall vibration and sound wave is proposed. High sensitivity sensor are installed outside the pipeline to monitor the signal that may threaten the pipeline safety, so as to realize the pipeline safety early warning. In this scheme, acceleration sensor and wall acoustic sensor will be used to monitor the vibration and acoustic events of the pipeline wall. When the safety events such as leakage, resonance and external damage occur in the pipeline, the detection and location of the safety events of the pipeline can be realized by detecting the vibration and acoustic waves of the pipeline wall.

4. System Realization of Ventilation Pipeline Safety Early Warning Technology

4.1 Composition of Ventilation Pipeline Safety Monitoring System

The main equipment of the system are monitoring terminal, leakage monitoring and positioning server. The monitoring terminal which are used to collect the acoustic and vibration signals inside and outside the pipeline and transmit them to the leakage monitoring and positioning server includes acoustic sensor, network time synchronizer, signal processor and other components. The monitoring terminal also has self checking function, which can detect and display the working conditions of sensors, network time synchronizers and other devices in real time. The hardware of the leakage
detection and location server is a PC server with high cost performance and stability, its software is the pipeline leakage monitoring software with independent intellectual property rights, which mainly gathers the monitoring terminal data from different locations to realize the monitoring terminal and system software, establish and maintain the communication channel of each terminal, and use the clock signal of each network time synchronizer to carry out accurate synchronization for the data sent [3]. The operation of the system needs the support of computer communication network. The monitoring terminal transmits the acoustic data to the server through the communication network. The existing communication network of SCADA is usually directly used. Using the existing optical fiber network and encrypting the data transmitted between the monitoring terminal and the server can ensure the reliability of communication in the public network. The system has strict data integrity check and error retransmission mechanism, to ensure that all data is accurately and reliably transferred.

4.2 Design Scheme of Ventilation Pipeline Safety Monitoring System

In this scheme, the pipeline safety monitoring system is designed for three ventilation pipelines. The system can monitor and locate the safety events such as pipeline leakage, blockage, resonance and so on, which can effectively guarantee the safe operation of the system.

4.2.1 System plan. 1) Sensor installation: install a group of wind pressure acoustic sensor array every 20 meters along the pipeline (composed of four acoustic sensors evenly distributed outside the pipeline cross section); install a group of wind pressure acceleration sensor array every 500 meters (composed of four acceleration sensors evenly distributed outside the pipeline cross section). The vibration signal is measured by piezoelectric acceleration sensor (ICP sensor). The traditional charge amplifier is built into the sensor, and all the high impedance circuits are sealed in the sensor, and output in a low impedance voltage way. The output signal of the ICP sensor cannot be directly obtained by the AD acquisition circuit. The array composed of 12 wind pressure acceleration sensors at the same node of the monitoring three ventilation pipelines can be designed to use the same constant current source for power supply to ensure the effectiveness, consistency and stability of the signal.

2) Installation of monitoring terminal: the length of each ventilation duct is 7868m, and one monitoring terminal is installed every 500m, totally 16 monitoring terminals are installed. In order to ensure the effect of noise shielding in the station and improve the accuracy of leakage monitoring, each monitoring terminal is connected with multiple sets of acoustic and vibration sensor arrays inside / outside the pipeline and on the pipe wall to realize real-time monitoring of pipeline leakage, blockage, resonance and abnormal operation; each monitoring terminal is responsible for collecting and processing a total of 4 * 3 = 12 wind pressure acceleration sensors and (500 / 20) * 4 * 3 = 300 wind pressure acoustic sensors Data.

3) Each monitoring terminal is equipped with a network timing data synchronizer to synchronize each monitoring data collection time.

4) One server and one set of monitoring operation station are set in the dispatching center.

5) The operation of the system requires the support of TCP / IP communication network, and each operation station, server and monitoring terminal needs an independent IP address. The operation station and server are placed in the monitoring center of the underground laboratory. The communication network of all monitoring terminals will be based on the optical fiber network that has been set up in the underground laboratory, and build a special optical fiber communication network according to the system design scheme and three ventilation pipeline topologies, using the serial topology structure of 16 Gigabit single-mode dual fiber optical transceivers.

4.2.2 System Scheme Design Basis. After ventilation pipeline leakage occurs, the high-speed flowing gas (the wind speed is 9.6m/s ~ 11.6m/s) in the pipeline will be ejected through the leakage outlet. At the moment of leakage, the gas ejection will form a shock wave, which generates acoustic signals with extremely complex frequency components, including infrasound signals (<10Hz), audible signals
(20Hz–20KHz) and ultrasonic signals (>20KHz). Audio signals and very weak infrasound signals will continue to be generated after the leakage occurs. The high frequency band of acoustic signal which propagates along the medium in pipeline, the wall of the pipeline and the air outside the pipeline attenuates extremely fast, and the action distance is very short. According to the equation of Qi and the equation of gas flow, and the parameters of the leakage area A, the absolute pressure in the container P1, the molar mass of the gas M, the molar gas constant R (8.314J/mol • K), the vessel temperature T1, the environmental absolute pressure P0, the critical pressure of the leakage gas P1, gas isentropic index k, etc. formula (1) of the gas flow leakage strength Qm can be deduced:

\[ Q_m = A \rho \frac{8M}{RT} \frac{k}{k-1} \left( \frac{P_0}{P_1} \right)^{\frac{k}{k-1}} \]

(1)

The gas is in subsonic flow at the leakage because of low operating pressure inside the ventilation pipeline. The pipeline status is monitored by continuously installing acoustic sensor arrays and acceleration sensor arrays at intervals along the pipeline. Once the leakage occurs, the sound wave in a certain frequency band generated in the pipeline will propagate through the gas in the pipeline, and will propagate to the nearest wind pressure acoustic wave sensor array at both ends through outside air. At the same time, it will propagate to the nearest wind pressure acceleration sensor array at both ends through pipe wall vibration. Use DOA estimate for the signal by a set of sensor arrays, or use spherical intersection calculation for the signal by two sets of sensor arrays, and then calculate the location of the leakage point according to the diameter of the pipeline and the arc surface. According to the sound power Lw (reference sound power is 1pw), directivity correction Dc (full directivity is 0dB) and the attenuation loss of the whole frequency doubling band when sound propagates from the point source to the receiving point A, the sound power at the receiving point Lgr can be calculated:

\[ L_{gr} = L_w + D_c - A \]

(2)

According to the attenuation of Adiv \( A_{div} = \frac{10\log(d/d_0)+11}{dB} \), \( d_0 \) denotes the reference distance of 1m caused by geometric divergence, the attenuation of Agr \( A_{gr} = 4.8 - (2h_m/d)^2 + (300/d)^{0.28} \), \( h_m \) denotes the average height from the ground of transmission distance (m), the attenuation of Aatm caused by adding barriers, other attenuation of Amisc caused by multidimensional effects, and the attenuation of Aatm caused by atmospheric absorption \( A_{atm} = \frac{a \cdot d}{1000} \). The value of A can be calculated:

\[ A = A_{div} + A_{gr} + A_{atm} + A_{misc} \]

(3)

To sum up, the temperature of an underground laboratory is not high all the year round. Calculated at 10 degrees Celsius, when the distance is 20 meters, \( A_{div} = 37dB \), \( A_{atm} = 0.856dB \) (for 4 KHz), \( A_{misc} = 4.47dB \) (for 0.1 meters from the ground), the total attenuation is about 42.126 dB; when the distance is 100 meters, \( A_{div} = 51dB \), \( A_{atm} = 3.28dB \) (for 4 KHz), \( A_{misc} = 4.76dB \) (for 0.1 meters from the ground), the total attenuation is about 59.04 dB. The preliminary calculation above shows that the main attenuation is caused by geometric divergence and atmospheric absorption as the distance increases (after 100 meters). The attenuation values caused by geometric divergence and atmospheric absorption are respectively exponential and linear with distance. The receiving sensitivity of acoustic sensor is mostly in the range of -48dB ~ -60dB. In order to make the acoustic sensor receive the medium and low frequency acoustic wave produced by leakage more effectively, a group of wind pressure acoustic wave sensors are set up along pipeline every 20 meters. In addition, previous test results show that the effective distance of the accelerometer is about 1000 meters when collecting pipeline wall acoustic signals. Therefore, a group of wind pressure acceleration sensors are set up along pipeline every 500 meters.

4.2.3 System Test Plan. Through selecting some typical test points of one of the three ventilation pipelines for test and verification, three test holes are opened at the air inlet of the top air duct, the middle section and the two groups of sensors at the end of the pipe. Each test hole is provided with a hole plate with a leakage aperture of 6mm, 12mm, 20mm, 25mm and 30mm. The air inlet of the air
duct is characterized by the maximum wind pressure and noise, the characteristics of the end of the pipe are the minimum wind pressure and noise, and the characteristics of the middle section are that the wind pressure and noise are both moderate. The system parameters can be optimized by testing the different leakage aperture of the three typical test points, so as to optimize the system performance. The installation diagram of needle valve for typical test points is shown in Figure 1:

![Figure 1. Schematic Diagram of Leakage Test Scheme for Wind Pressure Monitoring](image)

5. Conclusions
Through test and verification, the ventilation pipeline safety monitoring system can alarm and locate the leakage greater than 3% of the design flow of the pipeline in terms of detection sensitivity; the positioning error is less than 10 meters; in terms of response time, it can make correct leakage alarm within 300 seconds after the leakage occurs; in terms of data management, it has the storage and reference of historical leakage data of the pipeline for more than one year function. Due to the difference of field working conditions of the ventilation pipeline, the actual performance index of the system may be affected by the background noise, operating pressure and other factors of the corresponding pipe section[6].

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