Line average wind speed measurement system of roadway cross-section based on ultrasonic transit time Difference

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Abstract. Aiming at the problems of low measurement accuracy, poor adaptability, and lack of real-time online measurement methods for roadway section average wind speed, combined with the characteristics of roadway section, based on the characteristics of time difference caused by ultrasonic propagation in forward and reverse flow medium, high-energy ultrasonic transmission and long-distance transit are realized by adopting automatic tracking correction technology of transmission frequency and high-pressure pulse drive technology, program-controlled filter amplification technology and peak hold technology are used to achieve high quality processing of received signals. Accurate measurement of ultrasonic transit time is realized by adopting AD high-speed sampling time positioning technology, floating threshold time difference measurement technology and circuit time delay self-determination measurement technology, and finally realizes the measurement of the average wind speed of the roadway cross-section line. The measurement system is tested on the gas flow standard device, and the measurement accuracy meets and exceeds the requirements of relevant standards. Compared with the current technical means for measuring cross-section wind speed in roadways, the system has the advantages of one-time measurement of average line wind speed, high accuracy, strong adaptability and real-time on-line monitoring.

1. Introduction

Ventilation system is the "blood circulation system" of underground coal mining[1]. The occurrence conditions of coal seams in China determine that 97% of coal mines are underground mining. If the ventilation system fails, it will often lead to the potential safety hazard of insufficient air volume in the place where the air is used, and even lead to the occurrence of mine disasters[2]. Continuous and reasonable delivery of fresh air is the basis of mine safety production [3-4]. To achieve intelligent ventilation in coal mines and ensure reliable ventilation is the focus of intelligent construction in coal mines at present and in the future. Accurate monitoring of wind speed in roadway is an important means to understand the running state of mine ventilation system in real time, and it is also the key technology to realize intelligent ventilation.

At present, the point measurement method is used to measure the wind speed in the coal mine roadway, and there are some painful problems, such as the micro wind speed can not be measured, and the average wind speed measurement accuracy of the roadway section is low [5-6]. Wind speed measurement equipment based on ultrasonic transit time difference principle has the advantages of low measurement lower limit, wide measurement range, high precision and good linearity. In recent
years, it has been widely used in meteorological field and natural gas measurement field [7-11]. In the field of coal mining, several mine ultrasonic wind speed sensors [12-13] have appeared, which provide a solution for the measurement of micro-wind speed in coal mines. However, these sensors are still in the experimental application stage, and the single-point measurement method is used, which can not solve the problem of measuring the average wind speed of the roadway cross-section. In recent years, many scholars at home and abroad have carried out a lot of research work on the detection of the average wind speed of the cross-section of the roadway: Luo Yonghao has studied the wind speed distribution of the rectangular section roadway with four support methods of bolting, bolting and shotcreting, I-steel and flat wall [14], which provides a reference for accurately calculating the air volume and average wind speed of the roadway; Luo Guang obtained the position of the measured average wind speed line through research, and proposed the method of arranging sensors on the average wind speed line of the roadway to monitor the air volume of the roadway [15]; Zhang Qinghua et al. Designed a remote unmanned automatic measurement system for roadway wind speed by using mobile mechanism, point wind speed sensor and data transmission device [16], which realized the automatic measurement of roadway average wind speed instead of manual measurement.

The above research and design provide certain technical support and means for the measurement of the average wind speed in the roadway cross-section, and promote the development of the accurate measurement technology of the wind speed in the roadway, but the overall technical universality is insufficient, the measurement accuracy is low, and the real-time monitoring can not be realized.

In view of the current problem of measuring the average wind speed of roadway cross-section in coal mines, considering the universality of the application of technical equipment and the accuracy of measurement, based on the characteristics of time difference produced by ultrasonic wave in the process of forward and reverse flow propagation, through high-energy pulse driving, adaptive processing of received signals and high-precision time measurement technology. An ultrasonic measurement system for the line average wind speed of the roadway cross section (hereinafter referred to as the measurement system) is designed. Ultrasonic probes are installed on both sides of the tunnel to measure the average wind speed on the sound channel line continuously and in real time. The device is suitable for being installed in a roadway with any shape, can accurately measure the average flow velocity of any roadway cross section by arranging a plurality of measurement sound channels and matching with a corresponding fitting algorithm, does not affect the passage of the roadway, and provides an effective and accurate monitoring means for the wind speed of the roadway for an intelligent ventilation system.

2. Principle of line wind speed measurement of roadway cross-section by ultrasonic Wave

Sound waves can propagate in the air because the particles in the air move in the same direction as their vibration. When the ultrasonic signal propagates in the flowing air, the propagation velocity will be superimposed with the air flow velocity. When the ultrasonic signal propagates downstream, the propagation direction is the same as the air flow velocity component in the roadway (see Figure 1). The sound velocity will be superimposed with the air velocity component. The propagation velocity increases and the propagation time shortens; During countercurrent propagation, the propagation direction is opposite to the air velocity component in the roadway (see Figure 1), the sound velocity will be superimposed with the negative air velocity component, the propagation speed will be reduced, and the propagation time will be lengthened.
Figure 1. Principle Diagram of Line Wind Speed Measurement of Cross Section of Roadway by ultrasonic wave (top view)

As shown in Figure 1, when ultrasonic probe A emits sound wave to ultrasonic probe B, the direction of sound wave propagation is the same as the air flow direction component in the roadway. The time when sound wave reaches probe B is as follows:

$$t_s = \frac{L}{C_0 + V \cos \theta}$$  \hspace{1cm} (1)

When the ultrasonic probe B transmits the sound wave to the ultrasonic probe A, the propagation direction of the sound wave is opposite to the air flow direction component in the roadway, and the time for the sound wave to reach the probe A is as follows:

$$t_n = \frac{L}{C_0 - V \cos \theta}$$  \hspace{1cm} (2)

In formulas (1) and (2), $C_0$ is the inherent propagation velocity of ultrasonic waves in the air, $V$ is the average air velocity on the sound channel, $L$ is the distance between the A and B probes, that is, the length of the sound channel, and $\theta$ is the angle between the sound channel and the side wall of the tunnel.

From the combination of (1) and (2), we can find:

$$V = \frac{L(t_n - t_s)}{2 \cdot t_n \cdot t_s \cdot \cos \theta}$$  \hspace{1cm} (3)

It can be seen from equation (3) that the average flow velocity $V$ is only related to $t_s$, $t_n$, $L$ and $\theta$. When the probe is fixed, the variable that affects the velocity measurement is $t_s$, $t_n$. Accurate and stable acquisition of $t_s$ and $t_n$ is the key to the design of measurement system.

3. Measurement system Design

The measurement system is composed of ultrasonic transducer, switch circuit, ultrasonic emission drive circuit, signal receiving and processing circuit, CPU, peripheral interactive circuit and power processing circuit. The system design framework is shown in Figure 2. The drive compensation circuit and the high-efficiency drive circuit form an ultrasonic transmitting drive circuit of the ultrasonic transducer and are used for transmitting high-energy ultrasonic waves so as to ensure that sound waves can reach the opposite ultrasonic transducer with higher energy; An ultrasonic receive signal processing circuit compose of a circuit time delay measuring circuit and a program-controlled signal amplifying circuit is used for provide high-quality signals for accurately measuring that arrival time of ultrasonic waves, a transducer receiving and transmitting switching circuit is used for realizing the conversion of the transmitting and receiving States of the ultrasonic transducers and realizing that two ultrasonic transducers share the same ultrasonic transmitting driving circuit and receiving processing circuit; The peripheral interactive circuit is mainly used for realizing the functions of data display, signal output, human-computer interaction, data storage and the like; and the power supply processing circuit is used for processing an external power supply and supplying the external power supply to each functional circuit in the system.
3.1 Design of ultrasonic transmitting and driving circuit

In the propagation process of ultrasonic wave, its attenuation is related to the frequency of sound wave, and its attenuation coefficient is very large when it propagates in the air [17]. In the case of a certain medium and frequency, the attenuation of acoustic signals increases with the increase of propagation distance. In this measurement system, the propagation distance of sound wave is the distance between two ultrasonic probes when the system is installed in the field, which should be able to cover the roadways of various widths in large, medium and small coal mines in China.

A 120kHz ultrasonic transducer is installed on a sliding block, the sliding block is placed on a sliding rail, one end of the slide rail is provided with a sound reflecting plate which is vertical and whose plane is parallel to the signal transmitting surface of the transducer. Keep the ambient temperature, humidity, emission voltage and frequency unchanged, so that the transducer emits ultrasonic waves to the sound reflector, and then cuts into the receiving state. Move the slider and test the electrical signal output when the transducer receives the emitted sound wave, and get the distance-amplitude relationship diagram in Figure 3.
Figure 3. Relationship between acoustic wave propagation distance and received signal amplitude

It can be seen from Figure 3 that the amplitude intensity of the ultrasonic received signal and the ultrasonic propagation distance show a power function relationship, and the signal decreases sharply as the propagation distance increases.

When the applied pulse frequency is the same as the resonant frequency of the ultrasonic transducer, the output ultrasonic energy is maximum. In practical application, the resonant frequency of ultrasonic transducer has a deviation of 2% ~ 5% from the rated frequency. In order to ensure that the ultrasonic signal has enough energy to reach the receiving transducer and output a highly identifiable arrival signal, the system automatically tracks and corrects the transmitting frequency in the ultrasonic transmitting drive circuit.

Figure 4. Schematic diagram of automatic tracking and correction of ultrasonic emission frequency

As shown in Figure 4, firstly, the PWM output pulse is made, and the pulse frequency is the same as the rated frequency of the ultrasonic transducer, driving the ultrasonic transducer to emit ultrasonic; After the ultrasonic wave reaches the opposite receiving transducer, the ultrasonic signal is converted into an electrical signal, which enters the peak holding circuit after being amplified and filtered; The AD converter collects the voltage, which is output by the peak holding circuit, converted into the corresponding digital signal and transmitted to the CPU; The CPU converts and saves the digital signal, and records the pulse frequency value of PWM output. Step tow, the CPU adjusts the output pulse frequency of PWM in small steps. Step three, compare the newly received signal amplitude with the saved signal amplitude. If the amplitude increases, replace the previously saved amplitude and frequency with the new signal amplitude and corresponding frequency; On the contrary, if the amplitude decreases, the CPU will adjust in the opposite direction and repeat the above operations until the received amplitude reaches the maximum; At this time, the pulse frequency output by PWM is the resonant frequency of the transmitting ultrasonic transducer. In a later period of time, the ultrasonic transducer will be driven to transmit according to this frequency. The signal power amplifier circuit adopts the transformer boosting method to realize the 500V high voltage drive of the pulse signal.

3.2 Design of Signal Processing Circuit for Ultrasonic Receiving

The ultrasonic signal is also affected by the gas pressure fluctuation and flow field disturbance, and the amplitude of the received signal fluctuates greatly, which will adversely affect the measurement of the ultrasonic arrival time [18]; the signal processing circuit itself also has a certain time delay, and the time delay will be in an unfixed state due to the influence of external environmental factors. In order
to realize the precise measurement of ultrasonic arrival time, the design of this measurement system adopts the technology of signal programmable amplification and filtering processing and automatic measurement and correction of circuit delay.

The programmable amplifier circuit is composed of VGA voltage-controlled gain amplifier, BPF band-pass filter, AD converter, DA converter, etc. The VGA uses AD603 chip of ADI company, and its gain adjustable range is 0-40 dB; the AD uses 12-bit converter with 50 MHz sampling rate; the DA is directly implemented by the function module of the CPU; The BPF is implemented by a voltage-controlled voltage source second-order band-pass filter circuit, and its circuit schematic diagram is shown in Figure 5.

![Signal program-controlled amplifying processing and filtering circuit](image5)

Figure 5. Signal program-controlled amplifying processing and filtering circuit

The ultrasonic signal output by the transducer is first amplified by the VGA, then enters the BPF for filtering, passes through the peak hold circuit, and is input to the high-speed AD converter, and the CPU analyzes and processes the sampled data. When the actual amplitude of multiple received signals is lower than the preset amplitude, the DA output voltage is controlled to increase to increase the gain of the VGA to realize the amplification of the ultrasonic signal. Otherwise, the gain of the VGA is reduced to achieve the attenuation of the ultrasonic signal, and then to achieve The waveform amplitude of the received signal is within the expected interval (Figure 6).

![Amplified ultrasonic receiving waveform](image6)

Figure 6. Amplified ultrasonic receiving waveform

The automatic measurement of circuit delay is shown in Figure 7. The change-over switch is switched on to the input end of the program-controlled signal amplification circuit, the CPU sends out a pulse with the same frequency as the rated frequency of the transducer through PWM, meanwhile, the TDC time measurement circuit is started to start timing, and the pulse enters the time measurement circuit after passing through the signal amplification circuit, the switching circuit, an amplification circuit and a filter circuit. The measured time is the delay caused by the above circuit. The obtained delay time is used for correcting the arrival time of the ultrasonic wave, so that the accurate measurement of transit time is realized.

![Principle of automatic circuit delay measurement](image7)

Figure 7. Principle of automatic circuit delay measurement
3.3. Ultrasonic time of arrival measurement design

This measurement system uses the "floating threshold" technology to measure the arrival time of ultrasonic waves. After entering the program-controlled amplification and filtering processing circuit, the amplitude of the received signal will stabilize within the expected range, and enter the AD converter through the peak hold circuit. Using the conversion data and sampling interval of the high-speed AD converter, the amplitude of each peak can be determined and the time coordinate, and finally get the complete waveform envelope data. Read AD sampling data, search for several local peaks before the maximum peak, compare these local peaks with the preset threshold K. When a local peak value is less than K and the subsequent local peak value is greater than K, it is considered that the P3 and P4 peaks of this time have been found, and the peak values of P3 and P4 waves V_{P3} and V_{P4} of this time are recorded. Considering that the processed ultrasonic receiving signal may still fluctuate in the peak amplitude due to the random disturbance of the flow field, the threshold value needs to be dynamically modified to adapt to the fluctuation of the next received signal peak value. The correction method is as formula (4).

$$K_X = K + \Delta V_{P3} + \Delta V_{P4}$$  \hspace{1cm} (4)$$

In the formula: $K_X$ is the next threshold; $K$ is the current threshold; $\Delta V_{P3}$ and $\Delta V_{P4}$ are the offsets of the current threshold relative to the peak amplitudes of P3 and P4.

After the P4 peak is locked, the zero-crossing time of the waveform corresponding to the P4 peak is queried forward through the AD sampling value, and the arrival time $t$ of the received waveform can be determined in combination with the sequence number of the peak, as shown in Figure 8. The whole time measurement process is performed in the CPU. Based on this method, the arrival time $t_s$ and $t_n$ of the ultrasonic wave in the forward and reverse propagation process can be obtained respectively. By substituting $t_s$ and $t_n$ into the formula (3), the average flow velocity on the channel line can be measured.

![Figure 8. Schematic diagram of ultrasonic wave arrival time measurement with floating threshold method](image)

4. System device testing and Analysis

In order to meet the requirements of roadway wind speed measurement and related standards, the designed measuring range of this measuring system is: 0.1 m/s ~ 16 m/s, and the designed measuring error is: when the measuring speed is less than 1 m/s, the error shall not exceed $\pm 0.05$ m/s; when the measuring speed is more than 1 m/s, the error shall not exceed $\pm 0.15$ m/s.

The project team selected a gas flow standard device to verify the performance of the measurement system. The standard device uses air as the measuring medium and the Sonic nozzle as the standard device. The uncertainty of the device is 0.3% ($K = 2$). The maximum output flow rate can reach
25000 m$^3$/h. The two ultrasonic measuring probes of the measuring system are installed on both sides of the inner wall of the test pipe section (on the cross-section of the central axis of the pipe), and the length of the sound channel is 10m. Air is sucked from the pipeline, and enters the DN500 test pipe section in the form of turbulent flow after passing through the DN500 rectifier pipe section, so the average velocity $V_c$ measured by the system on the acoustic channel line is the average velocity in the pipeline. The actual flow rate is divided by the cross-sectional area of the pipeline to get the actual average flow velocity $V_b$ of the pipeline. The measurement performance of the system can be seen by comparing $V_c$ with $V_b$. Figure 9 is a photo of the field test.

![Figure 9. Test Site Diagram](image)

The test steps are as follows: 1) Close the test pipe valve to ensure that there is no air flow in the test pipe section, so that the measurement value of the measurement system is 0; 2) Open the test pipe valve, start the gas flow standard device, and adjust the device flow to the flow value of the test point; 3) Wait for the flow rate of the standard device and the measured value of the measurement system to stabilize, record the measured values of the two, repeat three times, and calculate the average; 4) Convert the flow value of the standard device into a speed value.

The measured data are shown in Table 1.

| Standard flow (m$^3$/h) | Actual wind speed (m/s) | Measured average wind speed (m/s) | Measurement error (m/s) | Percentage error (%) |
|-------------------------|-------------------------|-----------------------------------|------------------------|----------------------|
| 11431.00                | 16.18                   | 16.04                              | -0.14                  | -0.86                |
| 8766.30                 | 12.41                   | 12.29                              | -0.12                  | -0.95                |
| 4338.90                 | 6.14                    | 6.22                               | 0.08                   | 1.28                 |
| 1139.20                 | 1.61                    | 1.63                               | 0.02                   | 1.09                 |
| 65.36                   | 0.09                    | 0.09                               | 0.00                   | 0                    |

It can be seen from the test data in Table 1 that the actual measurement performance of the system has reached the design goal, especially at low wind speed, the measurement performance is more stable and the measurement value is more accurate. Through the oscilloscope observation, the waveform of the ultrasonic receiving signal at low wind speed is clear and stable, as shown in Figure 9.

5. Conclusions

In this paper, the relationship between ultrasonic propagation distance and signal attenuation is analyzed by using the characteristics of time difference between the forward and backward propagation of ultrasonic in the medium, combining with the characteristics of large cross-section of coal mine roadway, and the high energy ultrasonic transmitting drive circuit is designed by using the automatic tracking correction of transmitting frequency and 500V high voltage pulse drive technology. The ultrasonic receiving signal processing circuit is designed by using the programmable amplifier and the independent measurement technology of circuit delay, and the arrival time of ultrasonic is measured by using the "floating threshold" technology. The ultrasonic wind speed measurement system suitable for the measurement of linear average wind speed in the cross section of coal mine
roadway is developed. The system was tested on the gas flow standard device, and the results showed that the lower limit of the system could reach 0.1 m/s, and the upper limit could reach 16 m/s. The measurement performance exceeded the relevant standards, which met the requirements of wind measurement in coal mine roadway, provided an effective detection means for accurate measurement of average wind speed in roadway, and improved the technical level of wind speed detection in roadway.

References
[1] Zhang Qinghua. Development status and Prospect of coal mine ventilation technology and equipment in China[J]. Coal science and technology, 2016, 44 (6): 146-151
[2] Zhang Qinghua,Yao Yahu,Zhao Jiyu.Status of mine ventilation technology in China and prospects for intelligent development[J]. Coal Science and Technology, 2020, 48 (2): 97-103.
[3] Zhou Fubao, Wei Lianjiang, Xia Tongqiang, et al. Principle, key technology and preliminary realization of mine intelligent ventilation[J]. Journal of China Coal Society, 2020, 45 (6): 2225-2235.
[4] Zhou Lihong, Yuan Liming, Thomas Rick, et al. Determination of velocity correction factors for real-time air velocity monitoring in underground mines[J]. International Journal of Coal Science & Technology, 2017, 4 (4): 322-332.
[5] Yu Yongning. Analysis on reducing wind measurement error of mechanical anemometer. Shaanxi Coal, 2019, v.38; No.181(02):123-126.
[6] Shao Wei. Application and analysis of pitot tube and mechanical wind meter wind measurement method in reality[J]. Management and Technology of Small and Medium-sized Enterprises (First issue), 2012, No.316(03):230-231.
[7] Liang Liang. Development of Ultrasonic Wind Measurement System[D]. Jilin University, 2016.
[8] Bucci G, Ciancetta F, Fiorucci E, et al. A low-cost ultrasonic wind speed and direction measurement system[C]. Instrumentation and Measurement Technology Conference. IEEE, 2013:505-510.
[9] Rao Jialong. Design of a high-precision and low-cost ultrasonic anemometer for mines[J]. Automation and Instrumentation, 2020, (11): 119-121+125.
[10] Tang Panliang. Design of Ultrasonic Anemometer[D]. University of Electronic Science and Technology of China, 2014.
[11] Zhou Chuanyun. Research on the key technology of high-precision low-low-limit ultrasonic wind speed and direction sensor[D]. China Coal Research Institute, 2018.
[12] Ran Xia, You Qingshan. Mine ultrasonic wind speed sensor based on time difference method[J]. Coal Mine Safety, 2015(7).
[13] Liu Lili. Design of ultrasonic wind speed and direction sensor for coal mine[J]. Industry and Mine Automation, 2014(9).
[14] Luo Yonghao. Theoretical research on the distribution of wind speed in roadway section and real-time diagnosis of coal mine ventilation system[D]. Taiyuan University of Technology, 2015.
[15] Luo Guang. Research on the distribution law of wind speed and precise monitoring of air volume in typical roadway section[D]. China Coal Research Institute.
[16] Zhang Qinghua, Zhao Xusheng, Yao Yahu, et al. Remote unmanned automatic measurement and monitoring system and method of wind speed in roadway: CN111648827A[P], 2020.
[17] Yang Yuzhi, Liu Yanping, Cui Pengpeng. Selection of Sensor Parameters in Ultrasonic Gas Flowmeter[J]. Instrument Technology and Sensor, 2009(11): 416-417.
[18] W. Kang, S. Lee, S. Lee, Y. Ha. Effect of ultrasonic noise generated by pressure control valves on ultrasonic gas flowmeters. Flow Measurement and Instrumentation, 2018, 60: 95-104.