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连动型抗干扰干涉具井下瓦斯浓度监测系统

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摘　要:针对井下甲烷浓度监控干扰大的问题,结合实时监测甲烷浓度的系统要求,设计角镜连动的自消震光学结构,构建了基于无线网络的实时数据通信系统.在干涉系统中,固定两个角镜位置,将两片半透半反镜用连杆结构同步旋转,由此产生光程差.由于采用了连杆结构,任意时刻引入的震动在两个分束镜上等量存在,其结果是差分值,可实现完全相消.由分析分束器的最大旋转范围计算得到系统的光程差变化范围.结合比尔朗伯定律,给出系统在井下工作的甲烷气体浓度最低检出限.分别在实验室及矿井主巷道中完成实验过程,通过化学反应法求得被测甲烷气体的标准浓度,与 WQF530 型光谱分析仪的测试结果作比较,结果表明:在实验室无干扰条件下,两种检测方法的相对误差均小于 1.0%;在井下实验中,传统光学检测方法受环境影响明显,相对误差大幅增加,而本系统测试结果基本稳定,具有较强的抗干扰能力及较高的稳定性.

关键词:干涉具设计;光谱检测;瓦斯气体浓度;抗干扰能力;稳定性
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Methane Concentration Monitoring System Based on Connecting Move Type Anti-jamming Interferometer Underground

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Abstract: To effectively monitor methane concentration in the underground, for interference large characteristics underground , combined with real-time monitoring for methane concentration requirements, self-eliminate vibration optical structure was designed with rectangular prism linked, and the real-time data communication system was constructed based on the wireless network. In interferometer system, the position of two rectangular prism were fixed. The two beam splitters with connecting rod so that it can rotate synchronously, and the optical path difference is generated by rotation. As a result of the link structure, the vibration introduced into the two beam splitters are present in equal amounts at any time. Because the results was calculated used the difference value, therefore, it can be completely destructive effect. By analyzing the maximum range of rotation of beam splitter, the optical path difference range of the system can be calculated. Then through Beer-Lambert law, methane gas concentration detection limit of the system was given in the underground. Experiment in the laboratory and in the main mine roadway were completed, the measured standard concentration of methane gas obtained through a chemical reaction, and the results was compared to test results of WQF530 type spectrum analyzer. The results show that under the conditions of non-interference in the laboratory, the relative error of two detection methods were less than 1.0%; In the underground experiments, the test results of conventional optical detection methods significantly affected by the environment, and relative error was greatly increased, but the test results of the system was stable. So it

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is strong anti-interference ability and stability.
Key words: Interference designed; Spectroscopy; Methane gas concentration; Anti-jamming capability; Stability
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0 Introduction

Domestic and international spectrum analyzer was widely used which included Michelson interferometer, Grating diffractometer, static Fourier transform interferometer, and so on[1-4]. Michelson interferometer is the most commonly used spectrum analysis equipment. By the move of the moving mirror optical path difference, to obtain the interference fringes, it can choose to scan the optical path length accordance with the spectral resolution. The system can get a large range of the optical path, but the moving mirror is the mechanical scanning structure, so the system is vulnerable to outside influence. Grating can be used in many applications, with the advantages of a simple and non-scanning structure[5]. But there is a problem that the diffraction fringes obtained by such methods, it affects the luminous flux, so has been limited in the detection of trace gases. Of course, when the concentration of methane gas is detected in outdoor, the system has low detection capabilities subject to the restrictions of the luminous flux. It was applied the Fourier transform relationship of space interference fringes and spectrum in Static Fourier transform interference system. Because there is no moving mirror, it was less affected by the environment, and the luminous flux was also larger. But the structure of the static interference destined that spectrum resolution capability is limited, because it can not indefinitely increase the geometric structure.

There are many products in spectroscopy device field based on this principle, but most can not be applied to the detection of trace gases in outdoor[6-7]. Improved the stability of the interferometer system using modified the structure of the interference system, and accuracy error caused due to vibration is minimized in the field environment. Retained scanning structure, provided enough the optical path difference to detect gases, it was a specialized used field spectrum detection system. In outdoor working the accuracy error of detection comes from jamming in the environment, so most spectroscopy device always used in the laboratory and would lose efficacy in field environment[8]. So it is important to design a kind of system with the feature of satisfied high luminous flux and high stability. Domestic and overseas there are many organizations researching spectroscopy device for detecting the concentration of trace gases. WILLIAM F and his working team promoted the stability of Michelson interference system by improving the interference structure, which has the same size of the mirror and beam splitters[9]. The ROCKTM Series of BRUKER Company developed a kind of interference structure with two rectangular prisms, two mirror, and one beam splitter[10]. It makes light to go back in the same optical path using rectangular prism, so the spectrum distribution function is affected a little, the minimum spectrum resolution is 0.003 cm^{-1}[11-13]. In a word, it is necessary to research a system with high spectrum resolution and high stability, and it can detect trace gases.

1 System design

In order to improve the stability and accuracy, the spectrum analysis method was used to calculate the concentration of methane gas, optical structure of rectangular prism linked was designed for getting interference fringes, and the concentration of methane gas was solved by the spectrum distribution function. The beam splitters was used as part of mechanical scanning instead of moving mirror for getting the optical path difference. The beam splitters are connected by two connecting rods, so the interference of vibration can be offset by each other. Derived the maximum angle of the forward rotation and reverse rotation, which is the maximum range of optical path. The experiments were carried out in the indoor and outdoor, compared with the experimental interference fringes with WQF530 type spectrometer. In the conditions of indoor without interference, the accuracy of WQF530 type spectrum analyzer is slightly higher than the system, but in a real environment with interference, the stability of the system was significantly higher. Due to the different accuracy of the spectral distribution function, the detection accuracy of methane gas concentrations is also affected. Therefore, the seismic design of the system can effectively offset the power deviation caused by external interference and half-width increases of the center wavelength, so the system is more suitable for field detection than conventional interference device by mechanical scanning.

The principle of interferometer system was shown by Fig. 1. When the laser was come into the interferometer system, the light is detached two parts with same energy, one part arrive M_2 mirror through beam splitter (it can be called light 1), and another one is reflex to rectangular prism ABC (it can be called light 2). Light 2 spread from plane AB to plane BC, at last it reach CCD camera by focus lens, while light 1 spread to M_2 and is reflex to rectangular prism DEF from plane DE to plane EF. Because of focus lens, it can be interfered by different lights, so interference fringes can be collected by CCD camera. The optical path difference of the interferometer system was obtained by rotary beam splitter. In the Fig. 1, the dotted line shows it is the beam path in initial position of the corresponding prism. When the connected prism 1 and the connected prism 2 rotate θ angle, the optical path changed, so it produces the corresponding optical path difference. When outside interference make the moving mirror 1 to shake producing a small variable, because of the connected of prism 1 and prism 2 it will produce the same amount of shake effects on the contrary from the prism 2. The theory can be completely eliminated, but in practice, due to the different connection there will be certain error, but it can greatly improve the anti-vibration ability of the system. When mirrors rotate θ angle, corresponding optical path difference is the offset of θ angle in the design, so we can further increase the scanning range of the optical path for improving spectrum resolution higher.

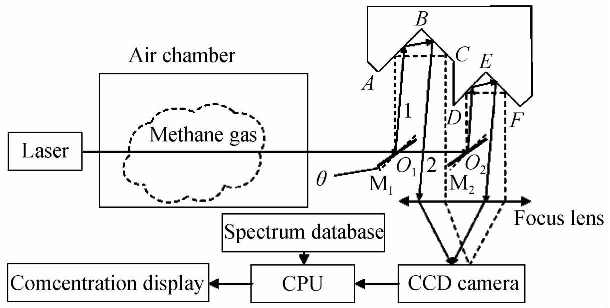

Fig. 1 Principle of the interferometer system

The main structure of the optical system is composed of beam splitter M_1, mirror M_2 and rectangular prism ABC and rectangular prism DEF. In the initial state, the plane mirror M_1 and M_2 is parallel to the plane AB and DE. The laser was divided into two beams of light through the beam splitter, through different paths to reach the focusing lens, the value of the interference in this process. Since the beam splitter rotation, two beams of light produce different optical path distance, thereby to produce a continuous change in optical path difference. When the presence of outside interference, the vibration introduced into the two beam splitters are present in equal amounts. Because the results was calculated used the difference value, therefore, it can be completely destructive effect.

2 Optical path difference function

2.1 Derivation of interference intensity

Assumptions: $AB=BC=a$, $DE=EF=a$, ABC and DEF is both rectangular prism, $CD=\sqrt{2}/2a$, according to the trigonometric relations, the value of the interference r is

$$r=\sqrt{2}a \tag{1}$$

In the process generate optical path difference, rotating θ angle, the corresponding optical path difference is

$$\Delta S=r\sin\theta \tag{2}$$

In accordance with the relevant principles of the focusing system, the optical path difference is

$$\Delta S=\sqrt{2}a\frac{h}{f} \tag{3}$$

Among them, the focal length of focusing lens is f, the real image height of object point is h.

Therefore, their phase difference is

$$\Delta\delta=\frac{2\pi}{\lambda}\sqrt{2}a\sin\theta=\frac{2\pi}{\lambda}\sqrt{2}a\frac{h}{f} \tag{4}$$

So at any point the interference intensity is

$$I(\sigma)=2I_0\left(1+\cos\left(\frac{2\pi}{\lambda}\sqrt{2}a\sin\theta\right)\right) \tag{5}$$

When $\frac{2\pi\sqrt{2}a\sin\theta}{\lambda}=k\lambda\ (k=0,1,2,\cdots)$, it is bright interference fringes.

When $\frac{2\pi\sqrt{2}a\sin\theta}{\lambda}=k\lambda\ \left(k=\frac{1}{2},\frac{3}{2},\frac{5}{2}\cdots\right)$, it is dark bright interference fringes.

2.2 Angle range calculation

In the interferometer system, optical path difference is produced by the rotation of beam splitters. Beam splitters can rotate clockwise or counter-clockwise, and it all could change the optical path. When it is clockwise rotation, through the triangular relationship the maximum rotation angle is

$$\theta_{max}<\arctan\frac{\sqrt{2}a}{2(\sqrt{2}a+h)} \tag{6}$$

When it is counter-clockwise rotation, beam from the surface BC could be reflected by the surface AB. The coordinate system is established by OO', and calculate the position of each point. B points is ($\sqrt{2}/4a$, $\sqrt{2}a+h$), C points is($3\sqrt{2}/4a$, $\sqrt{2}/2a+h$) and D points is($3\sqrt{2}/4a$, h).

So line AB could be shown by

$$y=x+\sqrt{2}a+h \tag{7}$$

And the line O_1A_1 could be shown by

$$y=-x\cot\beta \tag{8}$$

By Eq. (6) to (8), the maximum rotation angle can be calculated, it is

$$\theta < \frac{\pi}{2} - \operatorname{arccot}[13a + 2\sqrt{2}h + \sqrt{120(\sqrt{2}a+h)^2 + 64\sqrt{2}ha + 160a^2}]/7a \quad (9)$$

when $a = h$, the maximum rotation angle of beam splitter is

$$\theta_{\max}|_{\text{clockwise}} < 16.33° \quad (10)$$

Counter-clockwise to the maximum angle of rotation

$$\beta_{\max}|_{\text{counter-clockwise}} < 8.49° \quad (11)$$

Finally, it is known that the largest rotation angle, the system can calculate the optical path of the scanning range based on the ability of the rotation angle, and obtain the spectral resolution. The system can obtain the spectral distribution function by the Fourier transform from interference fringes detected, and can obtain the absorption rate of light intensity to corresponding wavelengths. By Bill-Lambert law it could calculate the concentration of measured gas, and the spectrum resolution will be a function of the concentration of measured gas.

3 Experiments

3.1 Experiments designed

The concentration of methane gas was detected in the laboratory simulation of in the mine, we separately did experiment to detect the concentration of methane gas in the chamber of the laboratory and emission source in the outdoor.

The interferometer system and its controller in the mine were shown by Fig. 2. The interferometer system was placed in the underground tunnel, and it obtained the concentration information of methane gas by spectrum analysis in the underground tunnel. By wireless transmitter module, the concentration information of methane gas is passed to the network control center. The concentration of methane gas for each point position was shown by display module in the processing center.

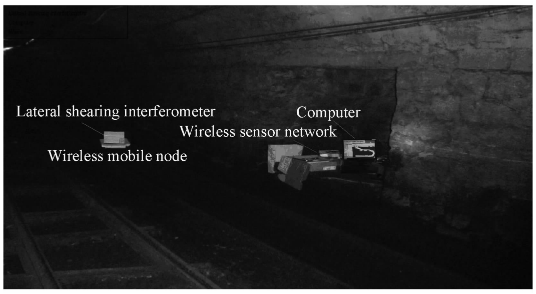

Fig. 2 The interferometer system and its controller in the mine

3.2 Experiments results

It is detected of the concentration of CH_4 gas in a laboratory chamber and field environments, every five minutes, the gas is collected in a measured region. The paper analyzed spectrum information at the same time through WQF530 spectrometer and the interferometer, inversion of the concentration of CH_4 information, and the data was shown by Table 1.

Table 1 The concentration of CH_4 data of the three methods

Time/min	Concentration of CH_4/($\mu g \cdot m^{-3}$)		
	Laboratory chamber		
Type	(A)	(B)	(C)
0	0	0	0
5	34.3	36.2	35.1
10	112.4	112.3	113.6
15	268.1	266.4	265.3
20	349.2	346.5	345.3
25	458.3	458.3	457.2
30	422.2	424.3	423.5
35	402.9	396.0	401.3
40	361.3	364.6	363.4
Time/min	Concentration of CH_4/($\mu g \cdot m^{-3}$)		
	Underground		
Type	(A)	(B)	(C)
0	0	0	0
5	29.3	25.2	28.2
10	85.2	72.3	81.2
15	212.5	184.2	197.5
20	303.8	286.4	296.3
25	413.2	427.6	403.7
30	383.2	386.8	385.2
35	313.4	292.4	306.4
40	247.4	223.3	247.1

Note: A is solving the concentration of CH_4 by chemical sampling and analysis; B is solving the concentration of CH_4 by WQF530 spectrometer; C is solving the concentration of CH_4 by the interferometer. The measured gas release, shut down after 30 minutes, and it is detected every five minutes.

At different times, using method of chemical sampling and analysis (A), WQF530 spectrometer (B) and the interferometer (C) to detect the concentration of CH_4 in the same region. Although method of chemical sampling and analysis can not achieve real-time detection, but its accuracy is 1 to 2 orders of magnitude higher than spectrometric method. Therefore, it looks as the standard results. Compared and calculated the ability to obtain the concentration of CH_4 by WQF530 spectrometer and the interferometer.

3.3 Data analysis

Method of chemical sampling and analysis was used for calibration. Experimental results was shown that in the laboratory air chamber, almost no outside interference conditions, the concentration of CH_4 detected by the two spectrum detection method was almost the same to method of chemical sampling and analysis. The relative error of two methods is less than

1%, and the precision of WQF530 spectrometer is slightly higher than the interferometer. However, in outdoor mode with interference conditions, it produces obvious errors of the concentration of CH_4 by WQF530 spectrometer, because of outside interference, and relative error ranged from 10% to 20%. And the relative error of the system is also lower than 5%. For the interferometer system, due to seismic design, so most of the outdoor interference is offset. So the concentration of CH_4 detected by the interferometer system is close to the true value. The spectrum data obtained from the spectrometer (spectral distribution function) can be seen, the center wavelength position has not changed corresponds to spectrum characteristics distribution of CH_4 using traditional spectrometer, but the amplitude decreases and the half-width increases due to outside interference. The spectrum data is basically the same in the interference environment and in the chamber of the laboratory using the interferometer system, so it is also close to the standard value when the inversion of the concentration of CH_4.

4 Conclusion

For long sampling time and the sentinel surveillance of traditional detection method of methane gas concentration shortcomings, designed the interferometer system. The system got change of optical path through rotation of the beam splitter, and got the range of the optical path for interference in the desired. The maximum clockwise rotation angle of beam splitter is 16.33° and the maximum counter-clockwise rotation angle of beam splitter is 8.49°. In indoor and outdoor experiments, the experimental results showed that detected in the indoor chamber of the test data of the two methods are close to the true value, and errors are less than 1%. In interference environment, the error of WQF530 type spectrometer became greatly, and more than 10%. The interferometer system error is below 5%.

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