Application of harmonic detection technology in methane telemetry

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Abstract. Methane telemetry plays a vital role in ensuring the safe production of coal mines and monitoring the leakage of natural gas pipelines. Harmonic detection is the key technology of methane telemetry accuracy and sensitivity, but the current telemetry distance is short, the relationship between different modulation parameters is complex, and the harmonic signal is affected by noise interference. These factors seriously affect the development of harmonic detection technology. In this paper, the principle of methane telemetry based on harmonic detection technology is introduced. The present situation and characteristics of harmonic detection technology are expounded. The problems existing in harmonic detection are analyzed. Finally, the future development trend is discussed.

1. Introduction
Methane telemetry can not only promote coal mine safety production, but also can improve the accident prevention and emergency response capacity. At present, the existing mine infrared methane sensor in the application of coal mine gas monitoring in China has the advantages of full-scale methane concentration monitoring, long calibration cycle in use, fast response time measurement and long life of sensing element, but the temperature, Pressure, humidity and others in the measurement environment impact on the measurement accuracy and higher cost of equipment and other issues [1]. At the same time the type of sensor is difficult to reach the upper corner of the mining face, tunneling face and the high-risk locations [2]. Therefore, with the development of high-performance laser generator and harmonic detection technology, a new type telemetry device of laser methane for the rescue team ahead of harmful gas detection, mined-out gas detection has become one of the research hotspots in the application of coal mine gas monitoring of China.

Harmonic detection technology as the core of the methane telemetry device, through the photoelectric receiver to detect the information containing methane concentration of the reflected laser signal, the use of phase shifter containing methane gas concentration signal to extract the various harmonics. It will be a good solution for the existing problems that based on the technology of methane telemetry device can make up for the current lack of mine gas monitoring, coal mine to achieve a full range of methane concentration monitoring[3].

In this paper, the principle of methane telemetry based on harmonic detection technology is introduced. The key techniques of gas absorption law, harmonic function, second harmonic measurement and harmonic ratio measurement in harmonic detection are introduced. Harmonic detection technology in the application of methane telemetry status and characteristics, and finally
from the application of the status quo and characteristics of the current point of view of some of the existing problems and trends.

2. The Principle of Methane Telemetry Based on Harmonic Detection

In the current gas telemetry, harmonic detection is used to improve the detection accuracy, and the central wavelength of the laser is swept through the gas absorption peak by wavelength modulation spectroscopy [4]. The high frequency sine wave is used to modulate the low frequency sawtooth wave related to the current amount. The frequency and power of the modulated wave are as follows:

\[ \nu = \nu_0 + \nu_1 \sin \left( \omega t \right) \]  
\[ I(\nu,t) = I_0(\nu,t) \left[ 1 + n \sin \left( \omega t \right) \right] \]  

Formula: \( \nu_0 \): laser light source center frequency; \( \nu_1 \): frequency modulation amplitude; \( I_0 \): laser is not modulated before the optical power; \( I(\nu,t) \): laser output modulation optical power; \( n \): light intensity modulation coefficient.

When the laser emitted from the laser is passed through the open space of the methane-containing gas, it is absorbed by the methane gas, and the absorption relation in the methane telemetry conforms to the Lambert-Beer gas absorption law [5].

\[ I_r = \eta K(R,A) I(\nu,t) \exp \left[ - \alpha(\nu)cL \right] \]  

Formula: \( I_r \): photodetector receives optical power; \( \eta \): reflectivity of the telemetry reflector; \( K(R,A) \): collection efficiency (the ratio of the received optical power to the transmitted power when no gas is absorbed and the diffuse reflectance is 1), which is related to the detection distance \( R \) and the receiving lens area \( A \); \( \alpha(\nu) \): the gas absorption coefficient, which is related to air temperature and pressure; \( L \): laser telemetry of the optical path.

There is \( \alpha(\nu)cL << 1 \), when the methane gas is a low concentration, the absorption coefficient \( \alpha(\nu) \) is relatively small, and the absorption optical path \( L \) is not very large. Formula (3) is developed by a series expansion method, and a linear part is taken

\[ I_r = \eta K(R,A) I(\nu,t) \left[ 1 - \alpha(\nu)cL \right] \]  

The gas absorption line is represented by a Lorentz linear function, and the intensity and frequency are both time functions [6], the linear function is brought into (4) and then propagated by Fourier series

\[ I_r = \sum_{n=0}^{\infty} A_n(\nu) \cos n\omega t \]  

Formula: \( A_n(\nu) \): fourier coefficients of c-th harmonic components of absorption coefficient.

After the normalization of the Lorentz linear function, the second harmonic coefficient is calculated [7]. Using the lock-in amplifier to extract the different harmonic components, which based on the formula (5). The gas concentration is proportional to the magnitude of the even harmonic component.

\[ I_f = \eta K(R,A) nI_0 \]  
\[ I_{2f} = \eta K(R,A) k\alpha_0 LcI_0 \]  

Formula: \( I_f \): first harmonic amplitude; \( I_{2f} \): second harmonic amplitude.

It can be seen from (6) and (7) that the first harmonic signal is proportional to the average power of the initial light intensity; the second harmonic signal is not only related to the initial light intensity, but also to the modulation coefficient, telemetry distance and gas concentration. The Therefore, the
concentration of the second harmonic amplitude or the second harmonic amplitude and the first harmonic amplitude can be used to invert the concentration of methane gas.

3. Analysis of Harmonic Detection

The input laser through the methane gas is effectively absorbed, and the output signal will be distorted in the methane telemetry study [3]. As the methane gas concentration increases, the output harmonics of the output signals increase. As the harmonic signal contains methane concentration information, so in the methane concentration telemetry theory of harmonic signal has been one of the focus of the problem [8].

At present, the methane telemetry device uses the detection signal to reflect the laser back, and through the gas absorption law and Lorentz linear function simulation of gas absorption coefficient normalization and Fourier series expansion, demodulation harmonic signal to reverse the concentration of gas [9]. At present, the harmonic detection is mainly through the measurement of low-order harmonic signal components, through the signal processing to calculate the open chamber methane concentration. Therefore, the focus of methane telemetry is how to accurately extract the methane absorption spectrum of the harmonic signal components. For the harmonic signal detection using band-pass filter or lock-in amplifier two options.

In the telemetry methane gas concentration, the laser signal received after receiving the detection target is limited. Therefore, the harmonic signal component is very weak. In the experiment, the band-pass filter can filter the out-of-band noise signal. However, in practice, this method should filter out the white noise and other noise in the harmonic signal as much as possible. This requires that the pass-band width is very narrow, since the quality factor Q of the band-pass filter is usually not more than 100, the pass-band width can't be narrowed indefinitely. Therefore, the amplitude-frequency characteristic curve is not flat enough in the pass band or the phase-frequency characteristic curve changes nonlinearly in the pass-band. [10] In order to compensate for the shortcomings of the band-pass filter in the weak signal extraction, the ambient light effects of the lock-in amplifier to remove the external noise and extract high-precision harmonic signal. Figure 1 shows that the principle of phase lock.

![Figure 1. Phase lock principle](image)

The phase-locked amplifier extracts the harmonics signals by using and referencing the reference signal of the signal at the same frequency. This technique shows excellent performance in terms of the density signal extraction that is small and submerged in the noise signal, greatly improving the detection signal-to-noise ratio for weak signals [11]. Therefore, the relevant areas of scientific research are widely used in phase-locked amplifier.

At present, analog and hybrid phase locked amplifiers are used in the detection of trace signals, because the temperature and phase shift of analog technology, the error of harmonic amplitude signal extracted by analog phase locked amplifier is larger [12]. With the rapid development of DSP technology, digital lock-in amplifier can convert analog signals to the digital domain for processing. The method has the advantages of small measurement error, large dynamic range, no temperature drift and bias effects [13]. Therefore, the methane telemetry is more important to use digital lock-in amplifier to demodulate each harmonic.

According to the ideal condition, the amplitude of the harmonic signal is proportional to the concentration of the methane gas. It is feasible to extract the second harmonic component separately in the harmonic detection. In the system, the temperature of the laser driver is and the current changes, resulting in laser light intensity and wavelength fluctuations [9]. This has a great impact on the measurement accuracy, the measured gas concentration is based on laser fluctuations and the existence.
of time-varying. The first harmonic is at the center frequency of 0, the second harmonic at the center frequency of the maximum absorption peak, by the formula (6), (7) analysis, the second harmonic than the value of the first harmonic signal and the concentration of methane gas is proportional to the value. Therefore, in order to overcome the second harmonic detection due to the use of various devices to introduce the noise signal and light source fluctuations caused by the impact [3]. At present, the more mature algorithm is to use the second harmonic signal and the first harmonic signal ratio method, through the ratio of the ratio of the relationship between the concentration value, accurate measurement of open environment in the methane concentration.

At present, in order to quickly extract the first harmonic and the second harmonic signal, accurately reflect the gas concentration and eliminate the measured signal and the reference signal between the phase difference, the direct acquisition of the target signal amplitude and phase [9]. Related research institutions designed a new orthogonal dual-channel digital lock-in amplifier, and has become a current research hotspot.

Through the methane telemetry signal generator for the lock-in amplifier reference channel with the measurement signal with the frequency of the sine, cosine two orthogonal reference input signal. The two reference signals are multiplied by the measured signal and then extracted by low-pass filter DC component, and then by square sum, square start operation, get the second harmonic signal [10]. Figure.2 shows that the quadrature digital phase lock amplifier.

4. Problems in Current Harmonic Detection
At present, the gas concentration measurement based on harmonic analysis mostly uses the gas absorption law series to start, taking its linear part approximation [14]. However, in the study of the current trace gas measurement, there is no deep study of the relationship between the three variables in the approximation condition of the above equation (4), which leads to a large error in the accuracy of the measurement of methane after telemetry. When the methane gas is telemetered in engineering use, the change of the surrounding medium will cause the diffuse reflectance to change and affect the accuracy of the gas received signal intensity and concentration inversion results.

At the same time in the methane concentration inversion test, due to the temperature and pressure range of large changes in the calculation of a certain type of line will bring the error. However, most of the current research is based on the Lorentz linear function, and does not explore the mechanism of harmonic linear function. So at different temperatures and pressures, should be based on the corresponding linear broadening of the specific circumstances to choose the appropriate line [15]. Therefore, it is very important to study the relationship between the line profile of methane absorption line and the change of ambient temperature and pressure. By learning the temperature and pressure knowledge of the linear function [15], the Lorentz line is mainly due to the collision between the particles when the gas pressure is large, which is related to the ambient pressure and the collision cross section. The Doppler effect caused by environmental temperature changes [16]. Therefore, the
absorption mechanism of the gas is different under different conditions, and should be described by different linear functions [15].

In the published literature, there is little influence on the influence of ambient temperature and pressure variation on the optimal modulation coefficient and modulation depth in the concentration inversion error [14]. At present, the test is to set a fixed frequency modulation coefficient and absorption spectrum half width at wavelength modulation, and calculate the modulation depth by Arndt normalization [8]. The harmonic optimal modulation coefficient \( k \) is obtained from the modulation depth \( m \) by the formula 7 in this paper. At present, after setting the optimal modulation coefficient under certain temperature and pressure, the inversion of methane concentration according to the empirical formula can't meet the requirement of high precision measurement. When the environmental change of methane telemetry is large, it is necessary to calculate the methane concentration according to the preset optimal modulation coefficient inversion. Therefore, it is necessary to consider the optimal modulation coefficient in the test process.

At present, when the harmonic signal absorbed by methane is extracted based on wavelength modulation, the spectral intensity is also modulated during the modulation process, resulting in a fixed phase angle between the modulation frequency and the modulation intensity. However, most of the current studies only consider the linear part of the light intensity modulation and ignore the non-linear part of the residual amplitude modulation (RAM), resulting in the detection signal line and system noise to a certain extent [8]. Considering the linear and non-linear effects of light intensity modulation, the signal modulation coefficient has a large degree of influence on the linearity and noise level of the harmonics to be detected. In a certain range, as the modulation coefficient increases, the asymmetry of the linearity increases and the baseline offset increases to bring about greater noise [14]. Therefore, the selection of the appropriate modulation factor is particularly important for improving the detection accuracy, usually with the maximum signal to noise ratio as the modulation amplitude of the choice to suppress the RAM noise [8]. Although the use of high harmonics for gas detection, the laser residual amplitude modulation RAM is small [17], but the current high harmonic signal is weak, extraction technology is difficult. Laboratory uses a lock-in amplifier with low-frequency detection function, in the harmonic analysis can only be directly used to extract a lock-in amplifier, the second harmonic.

At present, the second harmonic and first harmonic ratio method is adopted in the research of harmonic detection. This method effectively solves the influence of light intensity fluctuation and the removal of noise in the second harmonic method, but the method needs to use more Channel-locked amplifiers extract primary and secondary harmonics signals, which increases the complexity of the system and reduces the stability of the system [18]. In practice, due to the changes in the temperature and current of the laser, the output wavelength of the laser produces a drift, and the actual frequency produces a phase difference with respect to the central absorption peak of the methane. Therefore, in practice, the amplitude of the first harmonic at the center frequency \( N \) is not 0, that is, containing gas absorption concentration information. When using the second harmonic and the first harmonic signal ratio to reflect the gas concentration caused by the harmonic ratio method will bring measurement error.

In the process of inversion of methane concentration based on harmonic analysis, the change of ambient temperature and pressure change on the output harmonic amplitude of telemetry [15] is not perfect, and most of the research is based on the change of ambient temperature and pressure Discussion on the Influence of the Second Harmonic Peak. When the measurement of environmental conditions change more intense, often take to establish an equation to eliminate the temperature and pressure on the measurement results [15], through the simulation test to obtain part of the methane gas concentration, the least squares method to obtain empirical formula [19]. In the study of harmonic ratio method, the influence of environmental temperature and pressure variation on the first harmonic peak and the dynamic correction function are used in the inversion of methane gas concentration. So how to ensure the measurement accuracy in telemetry system is one of the main research directions.

5. Conclusions
Harmonic detection is a key technology of methane telemetry device, but the ambient temperature, pressure and other effects resulting insufficient of harmonic detection accuracy, higher price of digital orthogonal lock-in amplifier in harmonic detection, and it is difficult to extract the high-order
harmonic. These factors limit the widespread use of methane telemetry devices in mines. With the progress & development of science & technology, we can build a different temperature and pressure gas concentration inversion algorithm database and coal mine methane gas monitoring platform and the methane telemetry device based on harmonic detection technology gradually extended to the oil, Chemical, environmental testing and other fields, making it the future development of gas telemetry an important direction.

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7. References
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