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A background reduction method based on empirical mode decomposition for tunable diode laser absorption spectroscopy system

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ABSTRACT

In tunable diode laser absorption spectroscopy based trace-gas detection, the background fluctuation caused by interference fringes can significantly influence the system performance. To reduce the background fluctuation, empirical mode decomposition (EMD) is applied to process the measured signal in this paper. By analyzing the correlation coefficients between the original measured signal and each intrinsic mode function (IMF) acquired by EMD, the IMFs related to background are identified and removed. Lastly, the smoothed measurement values can be attained through a reconstruction procedure. The effectiveness of this proposed method was demonstrated by utilizing it to background and methane concentration measurements. After utilizing the proposed method, the standard deviation (STD) of the background measured in absence of absorbing gas was decreased from 1.9565 parts-per-million (ppm) to 0.1689ppm. The reduction of background fluctuation is achieved to a factor of 11. Results on the concentration measurements of 280ppm methane also indicate a precision enhancement, where the fluctuation reduced significantly with the STD decreased to 0.2537ppm. In addition, the proposed method exhibits a good performance on the running time. All the experiment results show that the proposed background reduction method has a great potential to be used in both laboratory and industrial gas detection.

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) has been widely used in gas detection because of its advantages of high selectivity, high spectral resolution, fast response time and so on [1–3]. However, most TDLAS systems are suffered from optical interference fringes which are mainly produced by multiple reflections or scatterings upon surfaces of optical elements [4,5]. Meanwhile, the variations of optical length and environment temperature also can result in optical fringes. Optical interference fringes are the major noises in TDLAS detection systems and they make background signals fluctuate in the form of an approximately sinusoidal variation. Under the influence of interference fringes, TDLAS systems have low

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detection precision and even fail to detect trace gas. Thus the studies on suppressing interference fringes and reducing the background fluctuation have attracted more and more attentions of the researchers.

To reduce the impact of interference fringes, many techniques have been proposed in past decades, such as using anti-reflection coating and wedged optical components [6,7], adding a Brewster-plate spoiler or a piezoelectric transducer into the optical path [8–11], employing balanced detection [12,13] or dual tone modulation [14–16], etc. These techniques improve system configurations and obtain different degrees of success in suppressing interference fringes, but they may add the complexity and the cost of detection system. Thus some researchers put their efforts into post-detection signal processing based on various digital signal filtering techniques, such as adaptive Wiener filter [17], Kalman filter [18–20], wavelet de-noising algorithm [21] and etc. In contrast to the techniques optimizing system configurations, these post-detection signal processing strategies are easy to implement, require no additional electronic, optical or mechanical elements, and can be adapted to any experimental configuration. In recent years, empirical mode decomposition (EMD) has received great attention in many application fields such as damage detection and biomedical signal processing, because of its superior performance in signal decomposition and de-noising [22–24]. Compared with the filtering techniques mentioned above, EMD has two outstanding advantages. One is that EMD is a simple algorithm with low computation complexity. Unlike Wiener filter and Kalman filter, EMD need not to solve the Wiener-Hopf equations and calculate the covariance matrix recursively which is a time-consuming process. The system based on EMD thus has a potential of yielding less response time. Another advantage is that EMD is an self-adaptive signal processing method and the EMD-based de-noising technique has less parameter need to be set compared with wavelet-based de-noising method which depends on more parameters such as mother wavelet type, decomposition level and etc.

In consideration of these merits, we introduce EMD method to TDLAS detection system in this paper to reduce the background noises. Since the gas concentration value measured by TDLAS detection system is a function of time, EMD is firstly applied to decompose the measured signal into intrinsic mode functions (IMFs). Then the correlation coefficients between the original measured signal and each IMF are calculated and the IMFs having bigger correlation coefficients are removed. Lastly, the remaining IMFs and the residual component of EMD are used to reconstruct signal. In this work, the effectiveness of this background fluctuation reduction technique is evaluated on the measured TDLAS data.

The succeeding sections of this paper are organized as follows. The theory of TDLAS gas detection and the proposed background fluctuations reduction method are described in detail in Section 2. Then in Section 3, we give an overview of the gas detection system used in the work. Section 4 is devoted to present the experiment results and discuss the proposed method in terms of its effectiveness on reducing background fluctuations, its running time and etc. Finally, a conclusion follows in Section 5.

2. Theory and method

2.1. Gas detection based on TDLAS

As a widely used technique in gas detection, TDLAS follows Beer-Lambert law. In near infrared region, when a narrow-band light passes through a sample cell containing an absorbing gas and the sample has a small optical thickness, i.e. $a(v)CL \ll 1$, the transmitted intensity $I(v)$ of the light can be written as [25–27]

$$I(v) = I_0(v)\exp[-a(v)CL] \approx I_0(v)[1 - a(v)CL] \tag{1}$$

where $I_0(v)$ is the incident intensity of the narrow-band light, C is the concentration of the absorbing gas, L is the optical path length through the gas, and $a(v)$ is the absorption coefficient at frequency v.

Typically, the frequency or the wavelength of laser diode is tuned by a high frequency sinusoidal injection current which is superimposed on a low frequency sweep current. This technique is called as wavelength modulation spectroscopy (WMS) and it can suppress some types of noises in TDLAS systems. When the laser diode is modulated by a sinusoidal injection current of frequency w, the instantaneous frequency can be defined as

$$v(t) = v_c + v_a \cos(wt) \tag{2}$$

where v_c is the center frequency of laser diode and v_a is the modulation amplitude [28].

When the detection system is kept at 1atm and room temperature, the collision broadening is dominated and the normalized Lorentz function is usually chosen to describe the absorption lines of the gas molecules [29], that is,

$$a(v) = \frac{a_0}{1 + (\frac{v - v_c}{\gamma})^2} \tag{3}$$

where α_0 is the absorption coefficient at center frequency v_c, and γ is the half width at half maximum.

The nth harmonic of detection signal can be extracted through a lock-in amplifier. In order to reduce the influence of light intensity on the measurement results, the ratio of the second harmonic component I_{2f} to the first harmonic component I_f is adopted in this paper. That is,

$$\frac{I_{2f}}{I_f} = ka_0CL \tag{4}$$