Efficient Digital Signal Process Strategy for TDLAS Gas Detection

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Abstract

With the introduction of DM laser technology, TDLAS gas detection techniques are realizing mass deployment. In this paper, we investigate signal processing techniques for TDLAS and introduce an equal weight sampling strategy to greatly reduce the data processing requirement. Theoretical analysis and experiments were conducted to investigate the sampling efficiency of such a sampling strategy, and concluded that the method can potentially reduce the noise by 11%.

1. Introduction

Tunable diode laser absorption spectroscopy (TDLAS) gas sensing is a highly sensitive and selective gas detection method. As we reported in 1st OFSIS, the introduction of DM lasers based on Eblana Discrete Mode (DM) laser technology enables the mass deployment of such technology.

Phase lock detection of second or high harmonic is an effective signal processing method used in TDLAS. This is traditionally implemented by analogue circuitry with nonlinear signal mixing. With the rapid performance improvement and cost reduction of on board digital processor and AD/DA convertor, digital processing is being adopted widely.

In most of the applications where digital conversion noise is acceptable the digital approach has a number of advantages compared with the analogue approach. The digital approach provides much more flexibility to implement sophisticated digital processing algorithms. The digital approach greatly simplifies the circuitry hardware design and debug and increased versatility. Some intrinsic issues of analogue approach such as zero drift can be solved easily. This is the main reason for the wide adoption of the approach.

Apart from digitalization noise, the weaknesses of the digital approach are discrete and limited sampling points and on board computation power required. The current digital phase lock detection implementation is basically a simple emulation of analogue approach and is not fully optimised with flexibility provided by digital approach to overcome the weakness. In this paper, we introduce new sampling and process strategy in order to solve those issues.

2. Sampling Strategy

The commonly used equal spacing sampling is the simplest emulation of the analogue approach. In this case, the detected single Q can be expressed as:

$$Q = \frac{\sum_{i=1}^{m} S(t_i)R(t_i)}{\sum_{i=1}^{m} R(t_i)^2}$$

(1)

Where $S$ and $R$ are signal and reference, $t_i = id$ is sampling point $i$ with equal spacing $d$.

Although such a sampling method is simple, it has two drawbacks: First, although the reference $R(t_i)$ can be pre-calculated, the multiplication operation $S(t_i) \cdot R(t_i)$ is still needed at each point at real time, this requires a relatively high computation power. Consequently a high cost and high power consumption on board processor will be needed. Secondly, the contribution of each sampling to detection result $Q$ is weighted by reference $R$. This means not all the sampling contribute to the result equally and some sampling where $R(t_i)$ approaches 0 are inefficiently using resources.
In order to overcome the above drawback, we introduce the equal weight sampling method. In such method, we increase the sampling points (reduce the sample spacing $d$) at the area where reference $R$ has higher absolute value and reduce the points (increase the spacing $d$) where $R$ value is close to 0. To ensure equal contribution to the result from each sampling point, we change the fixed spacing $d$ with spacing adjusted for each sampling point $d_i$ and let $R(t_i)d_i$ equal to all points.

$$Q = \frac{\sum_{i=1}^{m} S(t_i) \cdot \text{sgn}[R(t_i)]}{\sum_{i=1}^{m} |R(t_i)|}$$

Where $t_i$ can be determined by

$$R(t_i) = \frac{1}{d_i} \int_{t_i}^{t_i+d_i} R(t)dt$$

Where $t_i$ is dividing point between two sampling points and determined by

$$\int_0^{T_i}|R(t)|dt = \int_0^{T_0}|R(t)|dt$$

Where $T$ and $m$ are the period of $R$ and total sampling points within the period

Notice $t_i$ can be pre-determined with known reference $R$, only a point to point addition operation is needed at real time.

3. Noise Comparison

The detected value $S$ can be represented as useful signal $aR(t)$ and noise $n(t)$, where we assume $n(t)$ is Gaussian white noise. Under different sampling method, the signal always equal to $a$, but noise varies. For equal spacing sampling,

$$E\left\{Q^2\right\} = \alpha^2 + \frac{d^2}{T^2} E\left\{|n|^2\right\} \sum_{i=1}^{m} 2 \sin^2(\omega_i \tau_i) = \alpha^2 + \frac{E\left\{|n|^2\right\}}{m}$$

For equal weight sampling

$$E\left\{Q^2\right\} = \alpha^2 + \frac{mW^2}{T^2} E\left\{|n|^2\right\} = \alpha^2 + \frac{8}{\pi^2} \frac{E\left\{|n|^2\right\}}{m}$$

Comparing 5 and 6, the noise of equal weight sampling reduced 11% comparing with equal spacing.

4. Experiment

The experimental setup is shown in Fig 1. The signal generator is Agilent 33510B dual channel Trueform function generator, the Gaussian white noise is produced by computer and added to channel 1 with a 12 digit DA converter. The channel 1 and channel 2 output digitalized with 12 digit AD convertor as $S$ and $R$.

![Diagram of the Experimental Setup](image-url)
To avoid any impact from other uncontrolled noise, we use a sinusoidal wave of 1V amplitude as the useful signal and reference, and a Gaussian white noise with mean square root 1V.

Limited by the laboratory equipment availability, we use 10V single polarization AD/DC convertors. To avoid the negative voltage, we add a 5V DC voltage to both the signal and reference. Limited by the throughput of the convertor (20kHz), we set the signal and reference frequency at 32Hz. Fig 2 shows the data collected over 1 second period under 16kHz sampling speed.

![Fig. 2 The raw data of signal and reference](image)

Under the above condition, we made 120 measurement over 60 seconds. In each measurement we sample 4096 points over 500ms with equal distance and equal weight sampling methods respectively. By analysing the data in Fig 3, we found the mean square root noise voltage is 22.95mV for equal space and 20.94mV for equal weight. An improvement of 8.75% was observed.

![Fig. 3 Measurement Data over 500ms integration period for a) 4096 points b) 8192 points](image)

We then extend to sample period to 1 second and 8192 points and make 120 measurements over 120 seconds, the measurement results are plotted in Fig 3b. We obtained a mean square root voltage 15.53mV and 14.40mV for equal space and equal weight sampling. The improvement is 7.29%.

The above experiments show the equal weight sampling will indeed improve the sampling efficiency and reduce noise. The improvement is smaller than the 11% predicted. This may be affected by the limited sampling speed of the convertors. Although from noise bandwidth point of view the average sampling speed is the same for both methods, but the required instant sampling speed of equal weight need to be 1.6 times higher than that of equal space.
We also notice that the noise is higher than predicted for both methods. This is due to the correlation of noise between two sampling. In our theoretical model, we assumed the space between sampling is long enough and noise is totally random in each sampling. In reality some level of correlation exists between sampling, and such correlation makes different impact to different sampling method.

The noise does decrease with the increasing number of sample points, and the reduction is slightly larger than predicted. This can be contributed to AD conversion noise which was not considered in the model.

5. Conclusions

Both theoretical analysis and experiments show that in TDLAS digital phase lock detection signal process, the equal weight sampling method can not only greatly reduce the computation requirement of the system, reduce the microprocessor cost and power consumption, but also improve the sampling efficiency and reduce noise. Although in a passive sampling system, where signal is not actively modulated by reference, the higher ADC rate is required, in TDLAS where signal is directly modulated by reference, there is no additional ADC rate required.

As described, in this paper we present a more efficient sampling method with much less computation power required to implement digital phase lock detection in TDLAS. This method can be also more generically used in all other digital phase lock detection.

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