Self-adaptive CH_4 concentration detection system based on infrared spectrum absorption principle*

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Considering that the noises resulting from low modulation frequency are serious and cannot be totally eliminated by the classic filters, a novel infrared (IR) gas concentration detection system based on the least square fast transverse filtering (LS-FTF) self-adaptive modern filter structure is proposed. The principle, procedure and simulation on the LS-FTF algorithm are described. The system schematic diagram and key techniques are discussed. The procedures for the ARM7 processor, including LS-FTF and main program, are demonstrated. Comparisons between the experimental results of the detection system using the LS-FTF algorithm and those of the system without using this algorithm are performed. By using the LS-FTF algorithm, the maximum detection error is decreased from 14.3% to 5.4%, and also the detection stability increases as the variation range of the relative error becomes much smaller. The proposed LS-FTF self-adaptive denoising method can be of practical value for mid-IR gas detection, especially for weak signal detection.

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Recently, the detection technologies on inflammable and explosive gas concentration of CH_4 have made much progress[1-4]. The IR absorption detection method takes the advantages of wide measuring range, high accuracy and long lifetime, and it becomes a hot research issue in this field[5,6]. When the IR incandescence or IR LED as light source is used, the modulation depth decreases as the modulation frequency increases, so the modulation frequency is usually taken below 10 Hz. Due to this low frequency, the interference noises resulting from the light source, IR detector and electronic component, which include the $1/f$ noise, shot-noise and white Gaussian noise, are very serious. So eliminating these noises and increasing the signal-to-noise ratio (SNR) are very important for improving the detection accuracy. In the traditional design, the noises arising from the light path can be eliminated by using the single-source dual-channel method[7,8], and the noise caused by the electric circuits can be eliminated by using the hardware filter or classic digital filter. However, since the modulation frequency is so low, the $1/f$ noise interference and DC drift are hard to be denoised by these filters. Therefore, in order to remove the noises completely and improve the detection accuracy and sensitivity, we propose a novel self-adaptive IR gas detection system in this paper. The self-adaptive modern digital filter which is based on the least square fast transverse filtering (LS-FTF) algorithm[9] instead of the classic filter is introduced, and an additional noise channel besides the detection channel and reference channel is used.

LS-FTF algorithm is a self-adaptive filtering algorithm. It can estimate the statistic properties of the signal and noise during the working process and adjust its weighting coefficients automatically for achieving the best filtering results. The LS-FTF denoising principle of our detection system is shown in Fig.1. There are two needed input channels: one is the signal-detection-channel which receives the pure signal

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$d(n)$ from the IR detector and the other is the noise-detection-channel which only receives the noise signal $n_2(n)$. Because of the interference induced by the transmission circuits, the received signal $s(n)$ from the signal-detection-channel contains not only the pure signal $d(n)$ but also the noise $n_1(n)$. Note that $n_1(n)$ and $n_2(n)$ are not equal but have the same statistic property. $y(n)$ is the output from the LS-FTF digital filter, which is obtained by the weighting transformation on $n_2(n)$ with the N-th parameter-adjustable digital filter. $e(n)$ is the error output, which is the subtraction between $s(n)$ and $y(n)$. The weighting coefficient vectors are adjusted and recalculated by using the input noise $n_2(n)$, input signal $s(n)$ and the error output $e(n$-1), and then the output of the digital filter can gradually approach to the noise $n_1(n)$, and finally the error output $e(n)$ approaches to the pure signal $d(n)$.

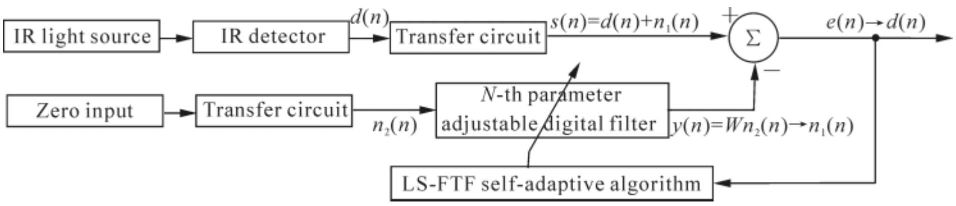

Fig.1 Realization diagram of LS-FTF self-adaptive algorithm

The error output is $e = s - y = d + n_1 - y$, and its mean square error is

$$E\left|e^2\right| = E\left|\left(d + n_1 - y\right)^2\right| =$$

$$E\,|\,d^2| + E\,|(\,n_1 - y)^2\,| + 2E\,|d \times (\,n_1 - y)| \quad . \tag{1}$$

Since $E|d(n_1\text{-}y)|$=0, we have $E|e^2|=E|d^2|+E|(n_1\text{-}y)^2|$. Define the weighting coefficient vector of the LS-FTF filter as W, then $y=W \times n_2$. Therefore,

$$E|e^2|=E|d^2|+E|(n_1\text{-}Wn_2)^2| \quad . \tag{2}$$

Since n_1 and n_2 are correlated with each other, there exists the optimal weighting coefficient vector W^* satisfying $n_1 \approx W^* n_2$. In this case, $E|e^2|$ becomes the smallest, and $e \approx d$.

To research the filtering performance by LS-FTF, Fig.2 shows the simulation on the polluted cosine signal with the frequency of 4 Hz, where the time-continuous signals are $d(t)$= 2cos(2δ×4t), $s(t) = d(t) + n_1(t)$, and $n_2(t) = 0.9n_1(t) + 0.1n_3(t)$, $n_1(t)$ and $n_3(t)$ are uncorrelated white Gaussian noises generated by MATLAB, and N = 2. We can find from Fig.2(b) that the error output $e(n)$ can well approach to the pure signal $d(n)$. This proves the favorable filtering function of the LS-FTF algorithm.

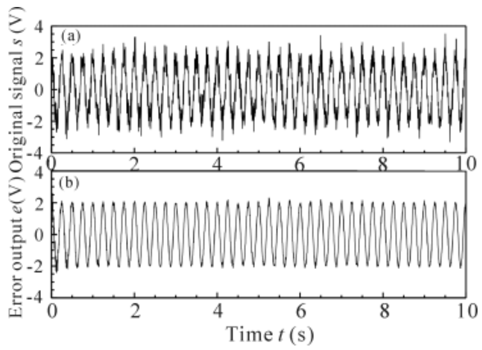

Fig.2 (a) Polluted signal *s*, and (b) error output *e* of the LS-FTF filter

In the following practical design, the selected detection gas is CH_4, the IR light source is incandescence with a modulation frequency of 4 Hz, and the detector is thermopile. Based on the detection principle of the single-source dual-channel method and Beer-Lambert law[10], the relation between the gas concentration C and output signals d_t and d_r from the dual-channel under the temperature T can be expressed as

$$C = M\big|_T \ln\frac{d_t}{d_r} + N\big|_T \ , \tag{3}$$

where M and N are the calibrating temperature dependent coefficients.

Fig.3 shows the diagram of the system based on single-source dual-channel detection method, where the dual-channel including the reference channel and detection channel is used. So d_t is defined as the pure output signal from the detection channel with the filtering wavelength of 3.31 ìm, and d_r is defined as that from the reference channel with the filtering wavelength of 3.9 ìm. As described before, the interferences induced by the shifts of light source and optical path can be eliminated by the ratio of d_t to d_r shown in Eq.(3).

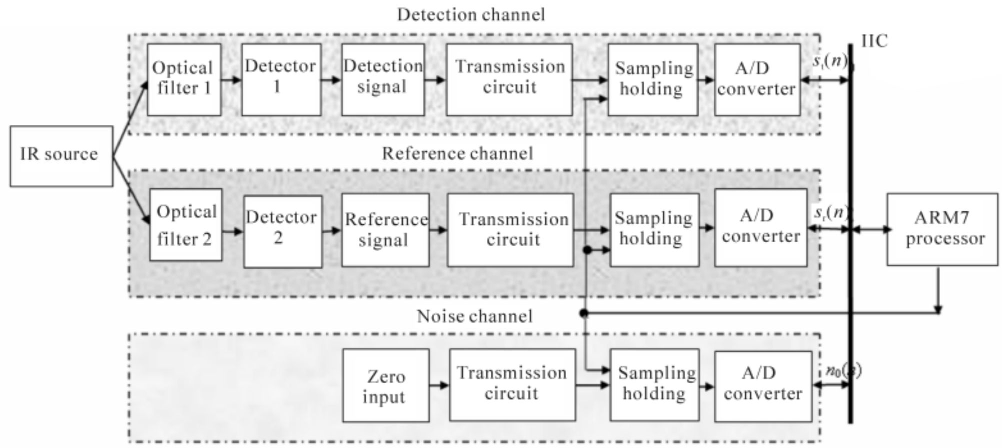

Fig.3 Diagram of the designed IR gas concentration detection system based on LS-FTF adaptive algorithm

Notice that since d_t and d_r can be polluted by noises, the detected results may be inaccurate. To totally get rid of the noises by using the LS-FTF filtering algorithm besides other hardware filtering methods, an additional noise channel as shown in Fig.3 is used besides the detection channel and reference channel. Considering the time synchronization of the LS-FTF algorithm, the sampling-holding modules of the three channels are controlled by one signal. Then the three samplings are synchronous. The time-discrete quantized sampling digital signal can be expressed definitely as $s_t(n)$= $d_t(n)$ +$n_t(n)$ for detection channel, $s_r(n)$ = $d_r(n)$ + $n_r(n)$ for reference channel, and $n_0(n)$ for noise channel, where n_t and n_r are not identical and they are both correlated to n_0.

The hardware diagram is shown in Fig.4, where the detailed module of the transmission circuit for one channel is only exhibited for simplicity. The ARM7 processor LPC2136 is used for realizing the light source driving, sampling and holding, A/D converting, digital displaying and LS-FTF digital filtering. The main design techniques are proposed in the following five parts.

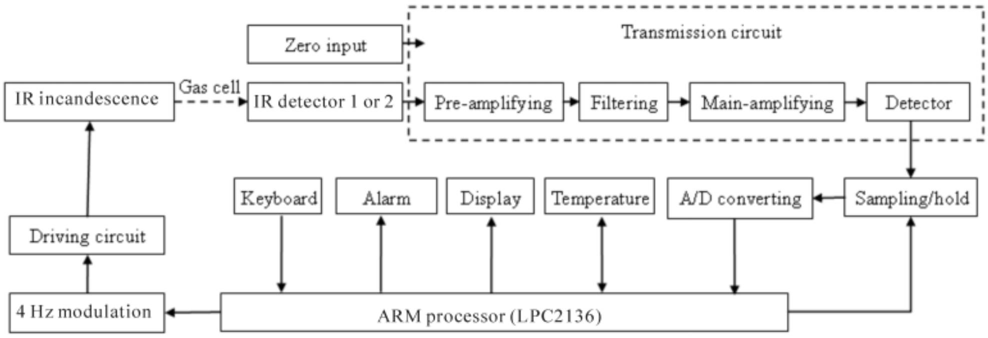

Fig.4 Detailed hardware diagram of the detection system

(1) Constant-current driver of IR light source

The stability of incandescence is the most important for concentration detection. The driving circuit must have constant current regardless of the power shift. The designed constant current driving circuit is shown in Fig.5, where the three-terminal integrated voltage regulator LM317 is used. The resistor R_3 is determined by

$$I_0 \cdot (R_2 + R_3) = 1.25\ \mathrm{V} \ , \qquad (4)$$

where I_0=115 mA is the rated current of the IR incandescence.

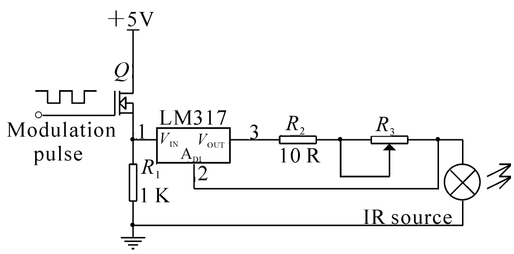

Fig.5 Constant current driving circuit for the IR source

(2) Low-noise pre-amplifier

To avoid influence of noises, the instrumental amplifier INA116 is utilized which possesses features including high common mode rejection ratio (CMRR), low noise, low voltage drift and low current drift.

(3) 4-Hz narrow band-pass filter

Since the interference and DC drift arising from the low-frequency noise can be relatively large, the filter to be designed must have narrow band-pass property for effectively avoiding these bad effects. We design a forth-order Butterworth narrow band-pass filter with the high precision and high speed amplifier OP37. The frequency response is exhibited in Fig.6. We can find that the 3-dB cutoff frequencies are 3.5 Hz and 5.4 Hz. This will effectively restrain the DC drift, 50 Hz interference and high-frequency noise within a narrow pass band of only 1.9 Hz.

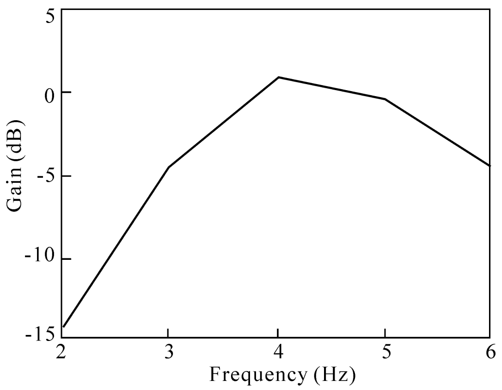

Fig.6 Frequency response of the designed 4-Hz narrow band-pass filter

(4) Sampling-holding and high-precision IIC A/D converter

For assuring the detection accuracy and decreasing the device size, we select the high-resolution, low power consumption self-adjusting 16-bit A/D converter ADS1100. It can meet the requirements for the detection accuracy and the minimum detection level. We select LF398 as the main sampling-holding module, which is capable of phase compensation and signal amplifying by adjusting its peripheral components.

(5) Temperature compensation

Since the absorption coefficient of the gas, the transmission efficiency of the optical filter, and the response efficiencies of the IR detector and IR source all change as the temperature varies[11], the detection results should be compensated for accuracy. For achieving this, the calibrating coefficients *M* and *N* shown in Eq.(3) under different temperatures are stored in the EEPROM of the processor. In detection, the initial calibrating coefficients under certain temperature ranges around the examined temperature, are read from EEPROM, and after linear-interpolation or cubic-spline interpolation, the interpolated coefficients are finally used for calculating the concentration value.

According to the hardware diagram shown in Fig.3, the system comprises three channels. Each LS-FTF calculation gets $s_t(n)$ from detection channel and $n_0(n)$ from noise channel or gets $s_r(n)$ from reference channel and $n_0(n)$ from noise channel as the two input variables s and n in the LS-FTF function prototype, respectively. Using the principle of LS-FTF, we compile the C-program using ADS 1.2 for LPC2136. The main detection procedure is described as follows. Firstly, parameters are initialized after powering on, and the synchronous sampling signal is sent to each channel after the start of the detection, and then the sampling values are held-up by the sampling-holder. The processor reads each channel value through A/D converter and transfers $n_0(n)$, $s_t(n)$ and $n_0(n)$, $s_r(n)$ to the LS-FTF digital filtering module in sequence for twice calculations, and then the denoised signals $d_t(n)$ and $d_r(n)$ are obtained. Next, the ratio of $d_t(n)$ to $d_r(n)$ is calculated. Finally, the gas concentration is determined and temperature-compensated by using this ratio and the interpolated coefficients *M* and *N*. The concentration result is compared with the pre-set threshold value. If the former value exceeds the later one, the sound and light alarms are made. Otherwise, the concentration result is only displayed with the LED. If the detection is stopped, the system returns back to the initial statue waiting for the next new round detection. Otherwise, the system starts the new round detection immediately obeying the above steps.

The open gas-cell is used for shortening the response time, and the half ellipsoid mirror is used for increasing the light intensity and detection sensitivity. The distance between the IR source and the IR detector with dual-channel is 8 cm. After soldering, packaging, programming and calibrating, the entire detection device is finally fabricated.

To check the performance of this system, the detection results on ten samples with standard concentration are shown in Fig.7. As a comparison, when the noise channel and LS-FTF algorithm are not used, the detection results on the same samples are also shown in Fig.7. We can observe from the comparison that the maximum detection error for the case without using LS-FTF algorithm is 14.3% while it is 5.4% for the case using LS-FTF. And also, we can conclude from the two error curves that the detection stability increases in the case using LS-FTF, since the variation range of the error is much smaller than that without using the LS-FTF.

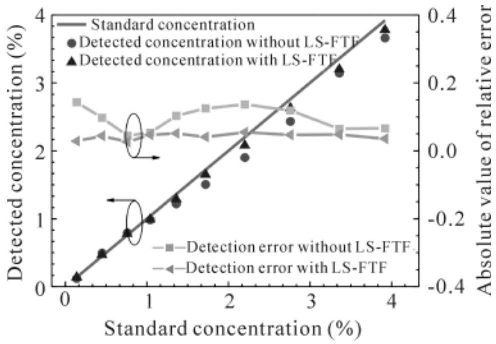

Fig.7 Precision curve and error curve between detected concentration and standard concentration under the cases with and without using LS-FTF

We propose a novel self-adaptive IR gas concentration detection system, which introduces the LS-FTF self-adaptive filtering algorithm in the software and introduces an additional noise channel in the hardware. Simulation results show that the LS-FTF algorithm has the advantages of simple realization and fast convergence for denoising. The constant current driving circuit of incandescence, low-noise pre-amplifying circuit, 4-Hz narrow band-pass filtering circuit and high-precision A/D converting circuit are designed. By the combination of software-based digital LS-FTF filtering and hardware-based filtering, the noise interference caused by the optical system and electrical system is effectively eliminated, and it is beneficial to decreasing the minimum detection level and improving the detection accuracy. Experimental results on CH_4 gas samples with standard concentration prove that this designed system has low minimum detection level, high SNR and high detection accuracy. The proposed LS-FTF self-adaptive denoising method can be of practical value for mid-IR gas detection, especially for weak signal detection.

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