  Journal of Water Supply: Research and Technology—AQUA | 60.5 | 2011

Practical Paper

Research on PWM applied in water turbidity measurement

Kai Zhang, Yu-jun Zhang, Gao-fang Yin, Zhi-gang Wang, Chao-yi Shi, Xue Xiao, Huan-bo Wang, Jing-bo Duan, Nan-jing Zhao and Wen-qing Liu

ABSTRACT

In this paper, three common measuring methods for the principles of water turbidity, namely, scattering, transmission and the ratio method are introduced. A method combined with modulation and demodulation techniques based on pulse width modulation (PWM) pulse for turbidity measurement using light intensity modulation is proposed. The experimental system that is, the realizing circuit of modulation and demodulation is described in detail. The experimental system was used to measure Formazine Standard Solution turbidity of different values. The experimental results are shown, and then turbidity values are calculated using the three methods. Through the analysis and comparison of the experimental results, it is shown that when using the ratio method combined with the modulation technique, the interference of background light can be eliminated effectively, so the measuring accuracy is significantly improved.

Key words | background light, micro controller unit, pulse width modulation, turbidity measurement

Kai Zhang
Yu-jun Zhang (corresponding author)
Gao-fang Yin
Zhi-gang Wang
Chao-yi Shi
Xue Xiao
Huan-bo Wang
Jing-bo Duan
Nan-jing Zhao
Wen-qing Liu
Key Laboratory of Environment Optics & Technology,
Anhui Institute of Optics and Fine Mechanics,
Chinese Academy of Sciences,
P.O. Box 1125,
Hefei 230031, China
and
Key Laboratory of Optical Monitoring Technology for Environment, P.O. Box 1125,
Hefei 230031, China
E-mail: *yjzhang@aiofm.ac.cn*

INTRODUCTION

Water turbidity is an important indicator of water quality. There are suspended colloidal particles in water, making the original colorless water nepheloid. This is called turbidity – how cloudy the water is. Turbidity level does not directly show general water quality, but increased turbidity, resulting from domestic and industrial wastewater, indicates a deterioration in water quality.

There are three basic turbidity measuring methods based on optical phenomena caused by the turbid liquid. They are the transmission, scattering and ratio methods. During measuring, the key question is how to avoid the interference of background light. The common method is completely closing the measuring devices to cover the background light; however, for online turbidimeters of embedded and inserted structures, in order to ensure the liquid flows into the probe freely, the closed structure can nott be used, so there has to be some disturbance from background light (Chen 2004).

A method which uses intensity modulation of a light source to radiate cloudy liquid, while the background light interference is filtered with signal processing to measure turbidity is introduced in this paper.

THEORY

Common methods of measuring turbidity

Transmission method

When light passes through turbid fluid, due to the absorption and scattering from the suspended matter in it, then the attenuation of the luminous intensity is compliant with the Lambert–Beer law:

$$I_T = I_0 \exp(-\tau L) = I_0 \exp(-KTL)$$

doi: 10.2166/aqua.2011.046

where I_0 is luminous intensity; I_T is the intensity of the transmitted light; τ is the attenuation coefficient, which has nothing to do with the luminous intensity and is caused by turbidity; K is the constant of proportionality; T is turbidity; and L is the optical path of the transmission (Liu & Wang 2007).

Scattering method

The scattering method is when a beam of light is passed through water testing samples and the scattered light intensity I_R of 90° can be expressed as follows (Song & Lu 1997):

$$I_R = \frac{KNV^2}{\lambda^4} I_0$$

where I_0 is the intensity of the incident light; N is the number of particles per unit volume; V is the volume of particles; and λ is the wavelength of incident light as a coefficient.

Under certain conditions, λ and V can be assumed to be constants, then the coefficient and the total number of particles per unit volume or the total volume is proportional, which means it is also proportional to turbidity:

$$I_R = K'TI_0$$

where T is water turbidity, and K' is another coefficient. Therefore, under the same incident I_0, scattered light intensity is proportional to I_R and turbidity, then turbidity measuring is turned into a scattered light intensity measurement.

Ratio method

According to Rayleigh's scattering theory and Mie's scattering theory, the relationship between scattered light and incident light can be expressed as:

$$I_S = \alpha N I_0 \exp(-\tau l)$$

where I_S is the luminous intensity of the scattered light; N is the number of particles that the water samples contain, which is proportional to turbidity; α is a coefficient related to the scattering function; and l is the scattering optical path. According to the ratio method between transmitted and scattering light, combined with the formula for calculating the transmission method water turbidity can be calculated as (Liu & Wang 2007):

$$\frac{I_S}{I_T} = \frac{\alpha N I_0 \exp(-\tau l)}{I_0 \exp(-\tau L)} = \alpha N \exp(\tau L - \tau l)$$

from the formula it can be seen that turbidity is only related to α and the optical path of scattering and transmission, because α, τ, l and L are fixed accurately, which eliminates the effect from the aging and instability of the LED light source to turbidity measurement hence improving the measuring accuracy.

The basic principles of PWM

Pulse width modulation (PWM) is a very effective technique, using microprocessor digital output to control analog circuits. It is used in many areas such as measuring, power control and communication transform, etc.

Each pulse column of the same width should be taken as a PWM wave. Its frequency can be changed by the cycle variation. The surge can be realized by changing pulse width or duty cycle. The voltage and frequency can be determined by control methods. Its duty cycle can be adjusted to control the circuit current. This approach enables the power supply voltage to remain constant when working conditions change (Shi & Liu 1997).

Analog modulation may be intuitive and simple, but it is not always economical or practical. Since it is difficult to adjust analog circuits as they drift easily over time. The precision analog circuit which can solve this problem may be very large and expensive. Additionally, they usually generate large amounts of heat and are very sensitive to noise, but through digitally controlled modulation circuits, system cost and power consumption can be reduced greatly. Therefore, PWM controllers have been included in many micro-controllers and DSP chips, which makes digital control easier.

SYSTEM DESIGN

Experimental system

As shown in Figure 1, this experimental system is made up of five parts: a PWM light-emitting unit, a detecting unit, a control unit, an angle measuring platform and a water sample trough. The schematic diagram of the experimental system is shown in Figure 2.

1. PWM light-emitting unit: The 850 nm infrared LED is used as the probe source, placed in the circle center of the shading tube, the front of which is connected with a scalable lens. The light that the LED emitted is almost parallel light after the position of the lens is set well, 1 kHz PWM signal which is generated by the internal DAC (digital-to-analog converter) of MCU ADuC841 is used to modulate the infrared light from the LED.
2. Detecting unit: Siemens BWP34 photocell is used as the receiving device, of which the peak wavelength is 850 nm. In order to prevent interference from background light, the detector is placed in the shading tube and a narrow band filter of 850 nm peak wavelength is placed in front of the tube. As a result the background light is reduced to under 5 mv. The scattering and transmitted light signals pass the pre-amplifier circuit, the filter circuit, the demodulation circuit and finally enter the MCU for turbidity calculation.
3. Control unit: The pulse modulation to the LED is realized by the MCU ADuC841, pre-amp gain control, the frequency selection control of selective amplifiers and A/D acquisition control of the signals.
4. The detection unit is fixed to the angle measuring platform, on which the intensity of the transmitted light and the 90° scattered light can be measured accurately.

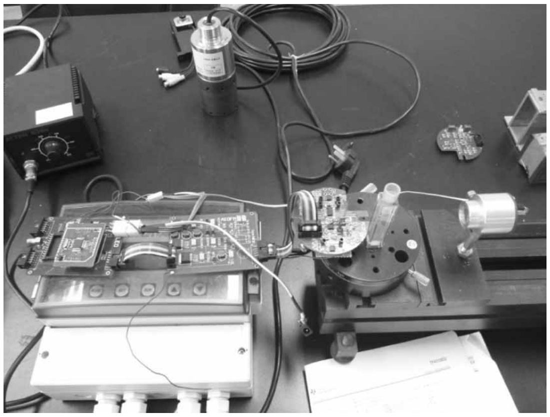

Figure 1 | PWM experimental system.

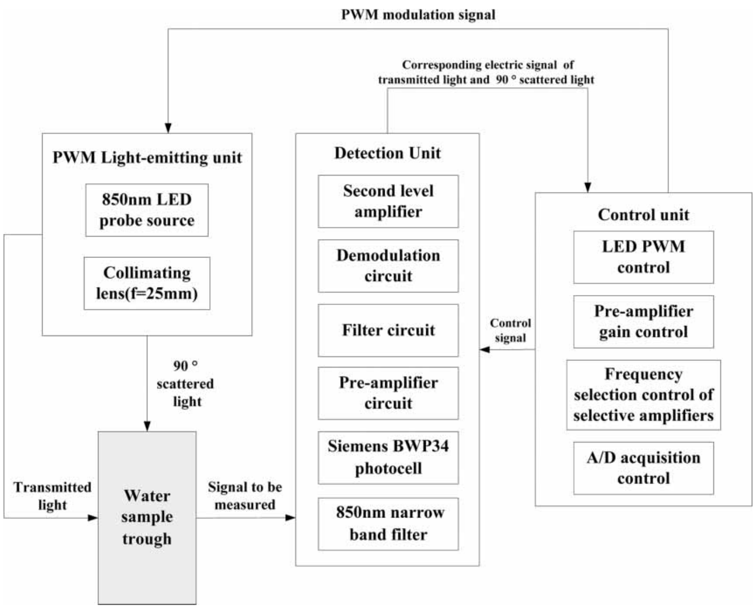

Figure 2 | Schematic diagram of the experimental system.

Design of the detection circuit

As Figure 3 shows, first, the PWM signal, as a carrier signal, turns the constant current source into high-frequency pulses through the analog switch. It is used as the power supply for the LED, realizing emitting source modulation. The PWM signal is produced by the pulse width modulator of MCU and therefore can be adjusted as required by programming the system freely. The frequency of the PWM square wave chosen by this system is 1 kHz with duty cycle of 50%. The waveform of the LED control signal is shown in Figure 4.

The pre-amplifier circuit is made up of an operational amplifier. It is for the I/V conversion of transmitted light and 90° scattered light signal. The signal waveform after the pre-amplifier circuit is shown in Figure 5 and it is still a square wave of 1 kHz with a duty cycle of 50%.

The band-pass filter which is four-order voltage-controlled voltage source, is used in the measuring circuit, since it is stable and easy to adjust its gain with high input impedance and low output (Yin *et al*. 2008). Its frequency is also 1 kHz. The signal waveform after the band-pass filter circuit is shown in Figure 6. It changed from the square wave of 1 kHz mentioned above to a sine wave of 1 kHz (fundamental of the square wave).

An average detection circuit is used in the demodulation circuit. Then a 10 Hz low-frequency signal is demodulated through the full-wave rectification and low-pass filter of the circuit (Hou 1994). The signal waveform after the demodulated circuit is shown in Figure 7 and it is changed to a direct current signal (effective value of the sine signal).

The demodulation signal is sent into the second-level amplifier, through which the signal conditioning is realized. After that, the remaining amplification is adjusted to meet

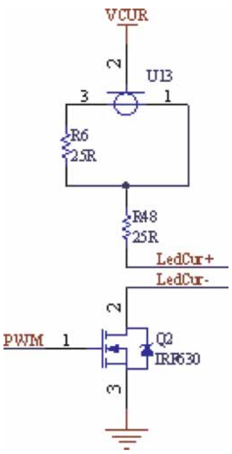

Figure 3 | Control circuit of excitation LED.

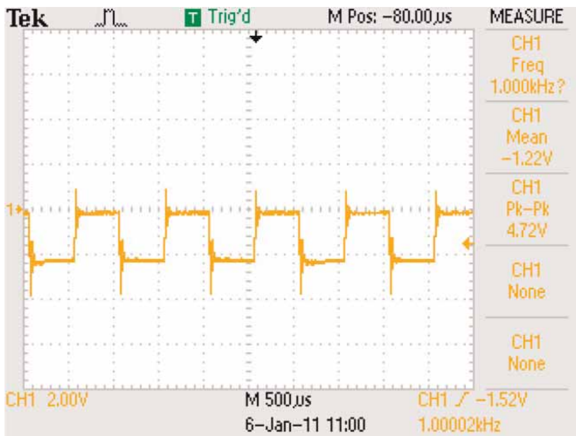

Figure 5 | Signal waveform after the preamplifier circuit.

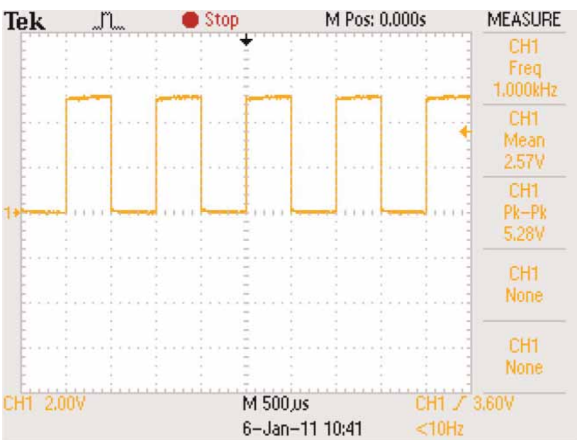

Figure 4 | PWM waveform to control LED.

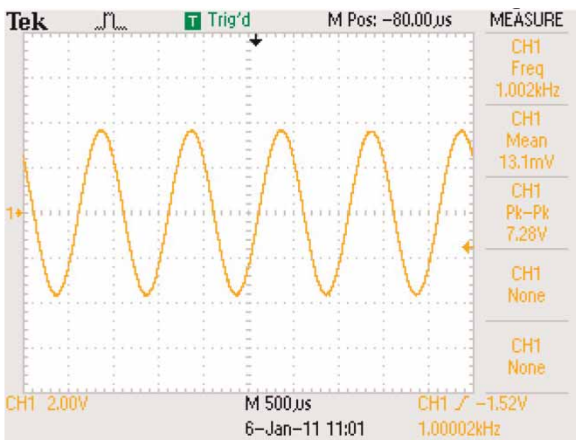

Figure 6 | Signal waveform after the band-pass filter circuit.

Figure 7 | Signal waveform after the demodulated circuit.

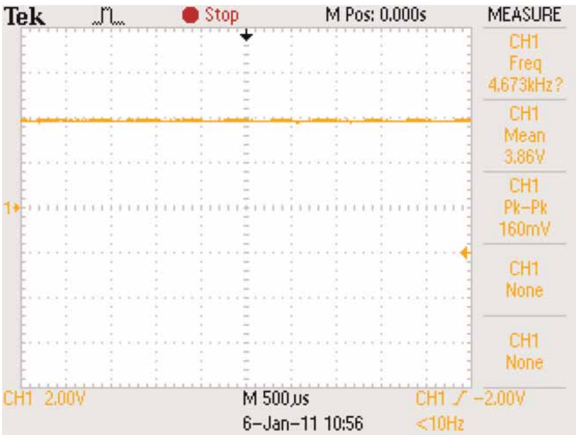

Figure 8 | Signal waveform after the second-level amplification circuit.

Table 1 | Turbidity measured with the PWM experimental system separately in three methods and then without it

Formazine standard solution (FTU)	90° scattered method (NTU)	180° transmitted method (NTU)	Ratio method between scattered and transmitted light (NTU)	Transmitted method without the system (NTU)
4	4.1	2.1	4.5	14.5
10	9.7	8.3	10.8	25.3
20	19.3	17.9	21.0	36.2
40	39.4	38.6	40.7	54.9
100	93.7	99.7	101.4	117.1
150	133.5	150.2	150.5	165.2
200	175.2	203.8	201.6	215.8
The average error (%)	5.74	11.55	4.25	80.20

Table 2 | Turbidity measuring repeatability with PWM in transmitted method

Formazine standard solution (FTU)	Number of measurements	Average data (NTU)	Standard deviation (NTU)	Coefficient variation
4	6	2.57	0.3327	0.1295
10	6	8.73	0.3011	0.0345
20	6	18.4	0.6633	0.0360
40	6	38.73	0.4967	0.0128
100	6	99.37	0.3559	0.0036
150	6	150.43	0.5046	0.0034
200	6	202.07	1.2307	0.0061

the demand of the A/D conversion, then the output signal and reference voltage of the A/D converter are matched (Yin *et al.* 2008). The signal waveform after the second-level amplification circuit is shown in Figure 8, which can be considered as the value of the transmitted light or the 90° scattered light signal.

RESULTS AND ANALYSIS

Table 1 shows turbidity values measured both with the PWM experimental system and without it. The values with the PWM system are shown in three methods. In Table 2, turbidity measuring repeatability with PWM in the transmitted method is shown from the average data, standard deviation, coefficient variation and number of measurements. From the two tables, it is easy to see that using signal modulation and demodulation to measure turbidity, background light interference can be excluded effectively, the accuracy of measuring is greatly improved, and the repeatability of the system is high enough to ensure long-term measuring accuracy. The performance of the system using the ratio method to measure is high or low turbidity is good. It should be noted that when only the scattering method is used, higher turbidity is measured inaccurately and conversely when only the transmission method is used, lower turbidity measurement is not precise enough, due to the difference between the transmission method and the scattering method. The former is suitable for turbidity measurement of wide range from common to high values, while the latter is for low and even ultra-low water turbidity measuring (Hou 1994).

CONCLUSION

Experimental results and analysis of the three methods above shows both environmental light and circuit noise interference can be effectively eliminated with light intensity PWM. Demodulation can be used for turbidity measurement, which can simplify the structure of the turbidimeter. It is easy to implement signal processing with MCU and the circuits mentioned above. It is not necessary for light intensity to be positive-cosine changed due to the use of PWM. It is effective when the periodic signal is of certain frequency, which makes the hardware structure easier. This approach is of practical significance for turbidimeters design of embedded and inserted structures.

ACKNOWLEDGEMENTS

The authors gratefully thank the National '863' Program of China under Grant (No. 2007AA061502, No. 2009AA063005), the Province's Technical Plan Project (No. 08010301107), the Natural Science Foundation of Anhui (No. 090415215) and the Foundation of Director of Anhui Institute of Optics and Fine Mechanics (No. Y03AG31144) for the support of the research.

REFERENCES

Chen, J. 2004 Measuring turbidity using light with modulated intensity. *Analyt. Instrument.* **4**, 39–42.

Hou, C.-G. 1994 Full-wave rectifier circuit tending to the ideal. *Trans. China Electrotechnical Soc.* **3**, 39–42.

Liu, C. & Wang, B.-F. 2007 Intelligent instrument for turbidity detection based on AT89S52. *Instrument Technique and Sensor* **12**, 59–61.

Shi, Y.-J. & Liu, H.-C. 1997 Principle and realization of phase PWM used in switching power supply. *Journal Inform. Engg Inst.* **3**, 44–48.

Song, Q.-M. & Lu, M.-G. 1997 *Water turbidity measurement. J. Shanghai University (Natural Science Edition)* **3** (1), 93–98.

Yin, G.-F., Zhang, Y.-J., Wang, Z.-G., Xiao, X., Jin, D., Zhao, N.-J. & Liu, W.-Q. 2008 Design of fluorescence detection circuit of alga classified instrument based on multi-wavelength LED. In the 15th session of the National Academic Report of Molecular Spectroscopy, 738106, 1–6.

First received 25 August 2010; accepted in revised form 27 April 2011