

Measurement of transparent liquid concentration based on ultrasonic grating method

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Abstract. In this experiment, ultrasonic grating method is used to measure the concentration of transparent liquid. The principle is that the liquid forms standing waves, namely ultrasonic grating, by using a signal generator. The monochromatic parallel light diffracted after entering the ultrasonic grating, and the sound velocity could be obtained by the spacing of diffraction fringes. The experimental equipment includes three parts: light source system, ultrasonic generation system and digital observation system. The experimental test shows that the experimental device can be used to measure the concentration of sugar water, salt water and other transparent liquid, with simple operation and high measurement accuracy.

Keywords: Ultrasonic grating, liquid concentration, digital micrometer eyepiece.

1. Introduction

The measurement of clear liquid concentration has application value in many fields, such as industrial food processing[1], chemical manufacturing, etc. At present, there are many methods to measure the concentration of transparent liquid, such as minimum deviation Angle method[2], optical rotation method, specific gravity method and so on. The above methods still need to be improved in the simplicity and accuracy of measurement. Among them, the first two methods use geometric optics[3]. In this experimental device, we use ultrasonic grating method based on wave optics which is more sensitive to the change of liquid concentration.

2. Measurement Principle

The principle is that the signal generator makes the liquid produce ultrasonic grating, and the monochromatic light diffracts after passing through the ultrasonic grating[4]. As shown in Figure 1, sound velocity can be measured through the spacing of diffraction fringes, and then the liquid concentration can be measured through the mapping relationship between sound velocity and liquid concentration. The experimental principle can be divided into three parts:

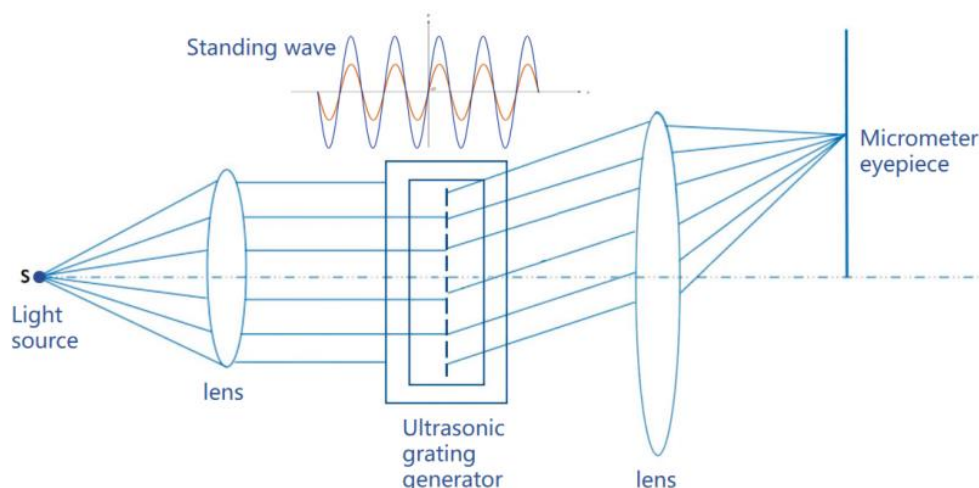


Figure 1. Schematic diagram of sound velocity measurement by grating method

2.1. Principle of liquid grating formation

The signal generator generates ultrasonic waves in the tank. When the ultrasonic wave propagates in the liquid, its sound pressure makes the liquid molecules change periodically, and the liquid generates periodic expansion and compression, which is also shaped into a standing wave. At this time, the liquid is equivalent to a grating. As shown in Figure 2.

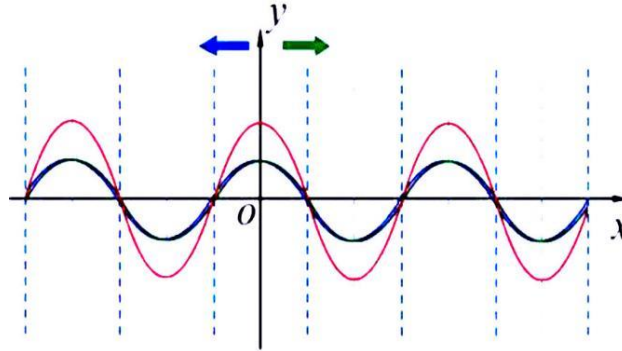


Figure 2. Schematic diagram of standing wave

Suppose the ultrasonic wave is transmitted in the liquid in the form of plane wave in the positive X-axis, and the form of the wave is as follows:

$$y_1 = A_m \cos \left[2\pi \cdot \left(\frac{t}{T_s} - \frac{x}{\lambda_s} \right) \right] \quad (1)$$

y_1 is the displacement away from the equilibrium position, A_m is the amplitude, T_s is the ultrasonic period, λ_s is the ultrasonic wavelength, t is the time when the ultrasonic occurs, and x is the displacement where the wave is located.

If there is a reflection plane in the vertical x direction, the ultrasonic wave is reflected by the plane and propagates in the negative x direction, and the form of the wave is as follows:[5]

$$y_2 = A_m \cos \left[2\pi \cdot \left(\frac{t}{T_s} + \frac{x}{\lambda_s} \right) \right] \quad (2)$$

When the positive and negative plane waves are superimposed to form standing waves, the offset of the equilibrium position is:

$$y = y_1 + y_2 = 2A_m \cos 2\pi \frac{t}{T_s} \cdot \cos 2\pi \frac{x}{\lambda_s} \quad (3)$$

At a certain time t after the formation of standing wave, particles on both sides of a node of standing wave rush to the node, making the vicinity of the node a dense area of particles. After half a period “ $t+T/2$ ”, particles on both sides of the node spread to the left and right[6], making the vicinity of the node a sparse area of particles. In other words, when the distance between the ultrasonic emitting surface and the reflecting surface is an integer multiple of half wavelength, the liquid in the device is equivalent to the liquid grating.

2.2. Principle of grating method for measuring sound velocity

When parallel light passes through the grating, in a direction perpendicular to the propagation of the ultrasonic wave, diffraction occurs.

$$\begin{cases} A \sin \phi_k = K \lambda \\ \sin \phi_k = \frac{\Delta L_k}{f} \end{cases} \quad (4)$$

ΔL_k is the distance from order zero to order K of the diffraction spectrum, A is the wavelength of the ultrasonic wave, f is the focal length of the lens, the focal length of the lens in this experiment is $f = 170\text{mm}$.

According to formula (4), ultrasonic wave length can be expressed as follows:

$$A = \frac{K\lambda}{\sin\theta_k} = \frac{K\lambda f}{L_k} = \frac{\lambda f}{\Delta L_k} \quad (5)$$

According to the expression of ultrasonic propagation velocity in liquid, the sound velocity can be calculated:

$$v = A\gamma = \frac{\lambda f \gamma}{\Delta L_k} \quad (6)$$

γ is the resonant frequency of the oscillator and the ceramic plate, λ is the wavelength of the light source.

2.3. Principle of sound velocity to concentration conversion

Since there is a linear relationship between sound velocity and concentration in salt solution, the corresponding concentration can be calculated according to the sound velocity - concentration empirical formula[7].

In this experiment, the calibration experiment results show that:

Taking salt solution as an example, the relation function is as follows:

$$p = (0.00076v - 1.2) \times 100\% \quad (7)$$

P (%) is the liquid concentration and v (m/s) is the speed of sound.

3. Device design and implementation

3.1. Overall experimental device

According to the above principles, we designed the experimental device. The instruments of the experimental device (as shown in Figure 3) from left to right are successively: digital micrometre system, parallel optical tube, tank, ground glass, light source and ultrasonic generating device. The actual picture of the experimental device is shown in Figure 4.

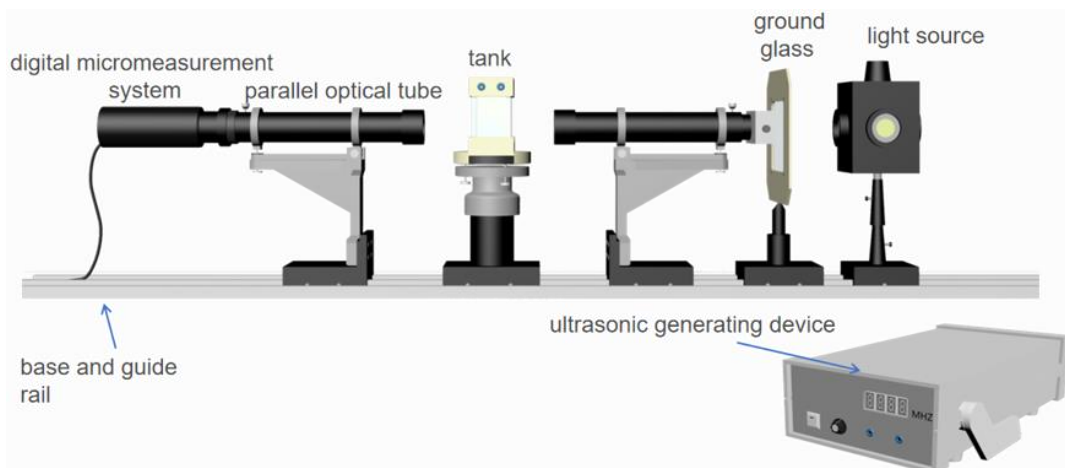


Figure 3. 3D modeling diagram of experimental device

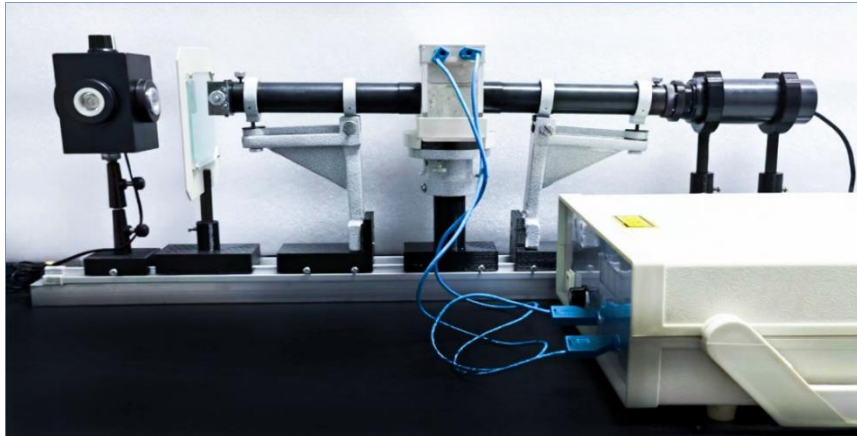


Figure 4. The actual picture of the experimental device

3.2. Device system composition

The project device can be divided into three parts: light source system, ultrasonic generation system and digital micromasurement system.

The light source system consists of a light source of 4-color LED lamp and two parallel light tubes. Four different wavelengths of light are used to calibrate the sound velocity and speed of different solutions, which can make the experimental results more accurate compared with only using a single color light source.

The ultrasonic generating system includes a signal generating device and a signal driving device. The signal generator is composed of the signal generator part and the signal power amplifier part, which can output stable and adjustable Megabyte frequency signal, so that the signal driving device produces resonance, and then forms standing wave.

The digital micromasurement system based on the principle of macro imaging is to place the CMOS camera sensor and digital micromasurement lens in the anti-light shell to reduce the interference of ambient light. And the observation software[8] of the upper computer is developed, which can obtain a clearer fringe image and improve the accuracy of reading compared with the traditional reading method of human eyes. Finally, the experimental device realized the reading of the transparent liquid concentration through a fringe pattern. As shown in Figure 5[9].

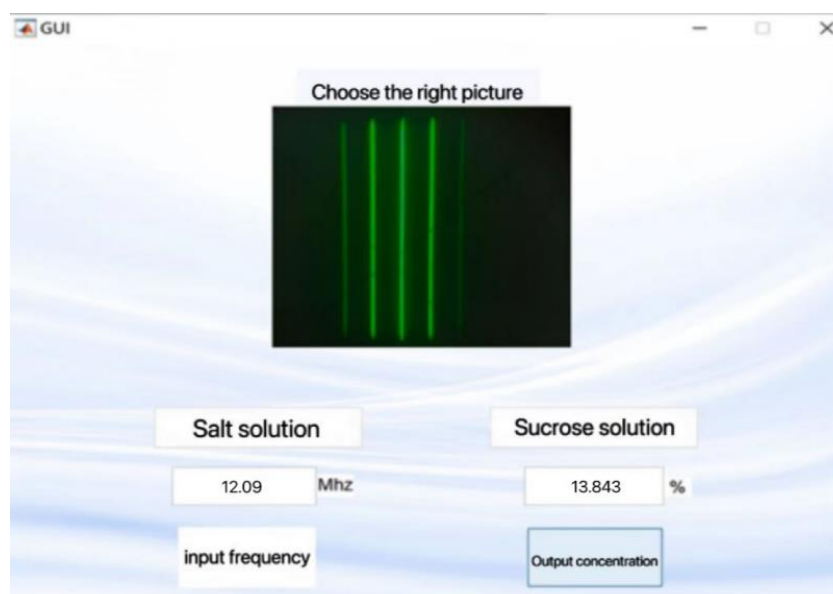


Figure 5. Digital observation system

3.3. Calibration experiment operation and data processing methods

Take the salt solution as an example, the salt solution is provided with a certain concentration at equal intervals, and pour the salt solution into the sink. The digital observation system read through the grating fringe spacing, and the fringe spacing is converted into the sound velocity through the relevant formula. After collecting data points several times, the relationship curve between salt solution concentration and sound velocity can be obtained. The procedure of calibration experiment for other kinds of solution is the same.

4. Experimental results and error analysis

4.1. Experimental results

We use the experimental to detect salt solution with theoretical concentration of 12.750%. The data recorded under light source with wavelength $\lambda = 546.07\text{nm}$ and lens with focal length $f = 170\text{mm}$ were shown in the table below:

Table 1. Salt solution concentration measurement records

group	Room Temperature $T(^{\circ}\text{C})$	Ultrasonic frequency $\gamma(\text{MHZ})$	Mean fringe spacing $\Delta L(\times 10^{-3}\text{m})$	Speed of sound $v(\text{m/s})$	Concentration $P(\%)$	Mean concentration $\bar{P}(\%)$	Relative Error $\delta(\%)$
1	25	10.70	0.568	1748.770	12.907		
2	25	10.68	0.567	1748.548	12.890		
3	25	10.68	0.567	1748.548	12.890	12.897	1.15
4	25	10.70	0.568	1748.770	12.907		
5	25	10.68	0.567	1748.548	12.890		

According to the measurement results, the relative error of salt solution with reference concentration of 12.750% is 1.15%, it is small and has certain observability.

4.2. Error analysis

4.2.1. Instrument error

(1) The error caused by the instability of the signal generator: when a stable grating fringe pattern can be formed in the measurement of the same concentration, the output frequency of the signal generator will have a disturbance of $(-0.03\text{MHZ}, +0.03\text{MHZ})$. For this phenomenon, we take the average value of the output frequency as the final calculated frequency, and then the error is generated.

(2) The uneven magnification of the camera in the field of vision, leads to errors in the reading of fringe spacing by the measuring software.

4.2.2. Environmental Error

(1) Environmental temperature, humidity, air pressure and other factors may affect the experimental results, causing certain errors.

4.2.3. Human Error

(1) When using the measuring software, the difference in the visual acuity of the measuring eyes may not lead to select the clearest fringe pattern, then throwing off.

4.2.4. Theoretical Error

(1) In the calibration experiment, there is a certain residual value in the fitting curve of solution concentration-sound velocity measured.

5. Experimental advantages and improvements

5.1. Experimental advantages

(1) Ultrasonic grating method adopted in the project takes advantage of the characteristic that wave optics is sensitive to concentration changes. Compared with commonly used geometric optics, it improves the accuracy of experimental results in terms of measurement principle.

(2) The digital micrometer system developed based on the macro imaging principle, displays the raster pattern on the computer screen, which solves the disadvantage of difficult reading in the micrometer eyepiece, replaces the traditional human eye reading method, and avoids human reading errors. In addition, the macro lens and CMOS camera were installed in the anti-light case, which enhanced the anti-light property of the device and improved the accuracy of the experiment.

5.2. Experimental improvements

(1) The reading of fringe can be improved more conveniently, and the transparent liquid concentration can be measured only through dynamic video without the need to adjust the grating fringe pattern.

(2) Expand this experiment. The image reading function of MATLAB in this experiment can be applied to the teaching of general physics experiments such as Fraunhofer single slit diffraction experiment, measurement of sodium light wavelength by double-prism interference[10], and Yang's double-slit interference[11].

(3) Add more types of solutions, increase the experimental database, and realize the measurement of the concentration of more types of solutions.

6. Prospect of experimental application

In this experiment, the traditional "disk" spectrometer is improved, enhance the accuracy of reading the grating fringe spacing, which can be used in university physics experiment class. The micrometer eyepiece and camera are integrated to enlarge the field of view of the lateral eyepiece, which further promotes the precision and convenience of the physical experiment. Intelligent reading of liquid concentration is achieved through computer software, which has considerable applications in the saltwater manufacturing industry, as well as industrial food processing plants, refineries, chemical plants and other operating sectors.

7. Conclusion

First of all, different transparent liquids are calibrated through experiments. The empirical curve was fitted. Compared with the existing data: the calibration experiments based on about 10 groups of data, we have conducted the 200 groups of calibration experiments. In the measurement system of the project, we designed and made the light source system, ultrasonic grating generation system and digital micromasurement system. Firstly, the four-color LED light of the light source system greatly increases the experimental data samples and increases the accuracy; Secondly, the ultrasonic signal generator is made, and the stable, continuous and adjustable signal output of mega-level ultrasonic signals is realized through the signal generator, signal power amplifier and transformer circuit and module, which greatly reduces the error caused by the instability of ultrasonic signals. Finally, the digital micromasurement system, through the combination of hardware and software, improves the convenience of use, and also avoids the disadvantage of the human eye reading error. According to the results of several experiments, the concentration error of sucrose solution is less than 1.50%, and that of table salt solution is less than 1.20%, both of which have a considerable error range.

References

- [1] Gu Xiaoping, Shu Zhenyu, Tang Jinsong. Design of high precision liquid concentration measuring instrument for food industry [J]. Journal of South-Central University for Nationalities (Natural Science Edition), 2007 (03): 51 - 53.
- [2] Chen Yuxing, Ma Zhenbin. Measurement of concentration and refractive index of NaCl solution by minimum deviation Angle method [J]. Experimental Science and Technology, 2010, 8 (06): 16 - 17+112.
- [3] ZHANG Jing. Experimental Research Based on Optical Measurement of Liquid Concentration [D]. Northeast Normal University, 2015.
- [4] Guo Shanhe, Gao Shuqin, He Yue. Measurement of transparent liquid concentration by ultrasonic grating [J]. Journal of Natural Science of Jilin University of Technology, 2000 (04): 34 - 36.
- [5] HE Chunle. Experimental Research on Sound Velocity Measurement [J]. Journal of Changzhi University, 2015, 32 (05): 40 - 43.
- [6] XUE Xiaotian, SONG Wentao, CUI Ganwei, YAO Huimin, ZHU Yunxia, GAO Jianping, LUO Zhanbin. Expansion of ultrasonic velocity measurement Experiment [J]. Physical Experiments of University, 201, 34 (02): 30 - 32.
- [7] Chen Yuxing. Effect of solute concentration and type on ultrasonic velocity [J]. Science and Technology Information, 20, 18 (02): 70 - 71.
- [8] Li Jun, Zhang Shuling, Shuai Jing. Digital Signal Processing Auxiliary Teaching System Based on Matlab GUI interface [J]. Information and Communication, 2020 (08): 283 - 284.
- [9] Zhao Jie, Li Yawen, Wu Xiaoyun. Design of signal and System Simulation Platform based on GUI [J]. Journal of Normal Science, 2022, 42 (12): 81 - 85.
- [10] Fang Yan, Liu Chengsen, Xue Taiping, Wang Yue, Yu Guohui, Sun Jiaoyue, Peng Jinjin, Song Jiaqi. Biprism interferometry using LED light source for wavelength measurement [J]. Experimental Physics of Universities, 20, 33 (04): 17 - 19+.
- [11] Ma Fengquan, Zhang Yuye, Wang Tong. Experimental exploration of double-slit Interference based on MATLAB [J]. Journal of Xianyang Normal University, 2022, 37 (02): 23 - 26.