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RATIOMETRIC IN-LINE TURBIDIMETERS: PRINCIPLE OF MEASUREMENT AND VARIANTS OF REALIZATION

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Various ways to realize ratiometric principle of liquid media turbidity measurement are reviewed. The principle allows to minimize in-line optical turbidimiters errors caused by soiling on windows of irradiators and photodetectors. As traditional as novel solutions are described. An idea to apply artificial neural networks for turbidimeters signal processing is stated. Some own practical results are presented.

Keywords: optical turbidimeter, ratiometric principle

1. RATIOMETRIC PRINCIPLE FOR LIQUID MEDIA TURBIDITY MEASUREMENT

Turbidity measurement is indispensable for water quality determination and as a regulating variable for many of the manufacturing processes.

Turbidity is the optical property of a liquid that causes light to be scattered and absorbed rather than transmitted in line direction. The cause of the light scattering is the presence of small particles having optical properties different from ones for the liquid medium. So it is possible to measure turbidity by light attenuation. Suppose a measuring device includes a light source and a photoreceiver dynamically positioned one towards another. Such type of turbidimeters is based on the relationship being analogous to the Lambert-Beer's law [1]. According to this law:

$$U_1 = k \cdot A_0 \cdot e^{-L_1 EC}, \tag{1}$$

$$U_2 = k \cdot A_0 \cdot e^{-L_2 EC}, \tag{2}$$

where U_1, U_2 - output signals of the photoreceiver corresponding to L_1, L_2 - distances between the source and the photoreceiver; A_0 - intensity of transmitted light; k - coefficient of transduction depending on transparency of windows and conversion transconductance of the photoreceiver; E - specific extinction coefficient; C - concentration of particles.

Looking for concentration C we can get from (1) and (2):

$$C = \frac{ln\left(\frac{U_2}{U_1}\right)}{E\left(L_1 - L_2\right)}. \tag{3}$$

We can see in (3) that unstable coefficients k and A_0 are abridged, one multiplier of denominator $L_1 - L_2$ is constant and the second multiplier E may be considered conditionally constant. Generally the specific extinction E depends on matter, size and shape factors of scattering particles. But commonly these averaged parameters are constant for a certain place or process and may be accounted for by calibration.

So it is unnecessary to provide high stability of the light source and the transduction channel (including optical path).

Very often scattered radiation is used for measuring of turbidity together with the direct attenuated radiation. Such turbidimeters are known as nephelometers. A photoreceiver of nephelometric signal must be situated at an angle of 90? with respect to radiation direction. Often nephelometric photoreceivers are parts of ratiometric turbidimeters. In that case the resolving formula (3) will be changed, but the general idea (cancellation of unstable coefficients k and A_0) will be the same.

Strict conditions for observance of ratiometric principle are possible if a turbidimeter has only one source and only one photoreceiver and it is possible to measure signals from the latter for two different distances (or two different angles) between the source and the photoreceiver. Such type of turbidimeters may be called single-beam, whereas other types - double-beam or multibeam. Double-beam turbidimeters may include, for example, the following combinations: 1 source + 2 receivers; 2 sources + 1 receiver; 2 sources + 2 receivers. The required condition for creation of a single-beam turbidimetr is availability to realize mechanical movement for periodical shifting of the source and the photoreceiver. On the contrary, the ratiometric principle for all multibeam turbidimeters may be provided without moving elements, though it is the special difficult task to hold coefficients k and A_0 in (1) the same as in (2).

2. IN-LINE TURBIDIMETERS: PROBLEMS AND FEASIBLE SOLUTIONS

In-line conditions require application of special engineering solutions in turbidimeters design. So in-line turbidimeters differ markedly from laboratory ones in their constractions, schemes and algorithms. In-line turbidimeters have to work often uninterruptedly twenty-four hours a day under high pressure, high velocity of liquid, high temperature, high aggressivity of medium.

But the main problem is the soiling windows of optical elements. If the function of a turbidimeter is to work in suspensions or in liquids containing solid matter particles only, this problem may be solved by application of mechanical wipers, pneumatic or hydraulic washers. In case when controlled medium contains adhesive particles (oil, gum) the mentioned means become fruitless: it is hardly to obtain the full clearance. For such mediums special solutions must be applied.

2.1. Turbidimeters with moving elements

Since it is impossible to avoid the soiling on windows, we must neutralize the influence of this detrimental factor.

One evident way to do that is to realize the ratiometric turbidimeter like one shown in Fig.1.

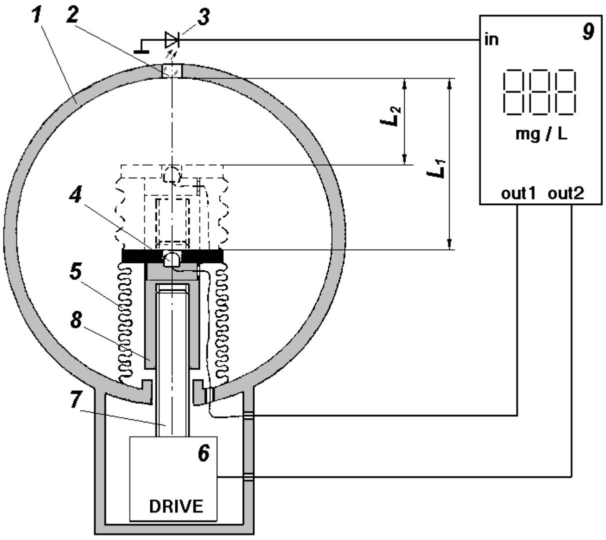

Fig. 1. Example of a ratiometric turbidimeter with a moving element

Its construction includes: measuring cell 1 in which transparent window 2 is fitted; photodetector 3; light source 4; sylphon 5; drive 6 (reversing electrical gearmotor); rotating element 7 (male screw); guide element 8 (female screw); controller 9. Distance variation between the photodetector and the light source is carried out by means of the drive 6, the moving element 7 and the guide element 8. The sylphon 5 serves as a delimiter for liquid and air mediums and provides leakproofness of the construction. Functioning of the turbidimeter is supported by the controller 9 which has one analog input for the photodetector signal and two control outputs: the first for the source switching and the second (bipolar) for commutation and reversion of the drive.

The turbidimeter operation comes to generation of software-controlled impulses on the controller outputs for the drive and the source, measurement of the photodetector output signals in corresponding time and calculation of particles concentration.

Signals from the photodetector output is measured twice for one cycle of measurement: for the distances L_1 and L_2. Calculation is carried out according to (3).

2.2. Turbidimeters without moving elements

The best-used variant for such type of turbidimeters is the combination "1 source + 2 receivers". Positional relationship between the photoreceivers and the light source may be rather various. In a certain case (under conditions if low concentration and strong soiling on windows take place) it is more preferable to use absorptiometric method, when the photoreceivers are positioned one after another in the light beam aperture. Sometimes it is more advantageous to realize nephelometric method, when the angle between axes of the photoreceivers may be 90° and more. In cases when dispersity of emulsion or suspension is not stable arrangement of photoreceivers as shown in Fig.2 may be useful. Here we use the phenomenon of directional distribution of light scattering depending on sizes of particles. For further processing the ratios U_0/U_1, U_0/U_2, U_0/U_3, U_0/U_4 must be used.

The serious disadvantage of all such turbidimeters is the errors caused by inequality of windows soiling. One good invention solving this problem and called as Four-beam pulsed light method consists in the following [2]. There are two light sources and two photoreceivers located as shown in Fig.3. The sources are pulsed consequtively. Two signals are detected at each of the photoreceivers: U_{1D} ,U_{2D} when the corresponding opposite source is active (absorptiometric signals) and U_{1S} ,U_{2S} when the scattered radiation from the side source takes place (nephelometric signals). Suppose k_1, k_2, k_3, k_4 are the coefficients of soiling for the corresponding windows as designated in Fig.3. If I_1 and I_2 are the intensities of sources, then the equations for U_{1D}, U_{2D}, U_{1S}, U_{2S} can be written as

$$U_{1D}= I_1 \cdot k_1 \cdot k_3 \cdot f_1(C), \tag{4}$$

$$U_{2D}= I_2 \cdot k_2 \cdot k_4 \cdot f_2(C), \tag{5}$$

$$U_{1S}= I_2 \cdot k_2 \cdot k_3 \cdot F_1(C), \tag{6}$$

$$U_{2S}= I_1 \cdot k_1 \cdot k_4 \cdot F_2(C), \tag{7}$$

where $f_1(C)$, $f_2(C)$ are transduction functions for absorptiometric signals and $F_1(C)$,$F_2(C)$ for nephelometric.

Evidently, the ratio $\frac{U_{1D} \cdot U_{2D}}{U_{1S} \cdot U_{2S}}$ will be free of unstable terms k_1 - k_4, I_1 , I_2 . So only the new function of concentration $R(C)$ will determine the result:

$$R(C) = \frac{f_1(C) \cdot f_2(C)}{F_1(C) \cdot F_2(C)} \ . \tag{8}$$

Another idea resolving the problem of inequality of windows soiling lays in creation of informational redundancy by means of photodetectors' arrays or arrays of "source-detector" pairs, statistical processing of signals and

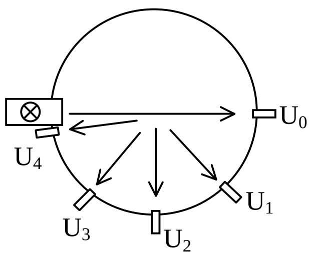

Fig. 2. Example of a nephelometric turbidimeter with several photoreceivers

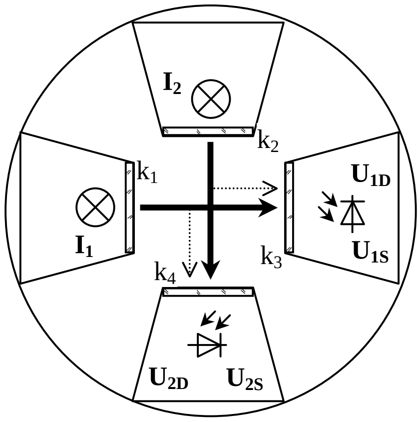

Fig. 3. Four-beam pulsed light method

subsequent operations with averaged values. Evidently, the random error reducing in that case is $\sqrt{N}$, where N is the number of channels. A measuring cell with such arrays of light sources and photodetectors is shown in Fig.4.

Even if glass windows 1 positioned ahead of arrays of light sources 2 and photodetectors 3 get different soiling on their working surfaces the average level of dirtying is rather constant. So after statistical processing and dividing the averaged signal from the short channel detectors by the averaged signal from the long channel ones we can get a soiling-independent result. Due to multiple backup elements such systems can work stably under conditions of very thick soiling. It will continue to work even in case of full closing of some discrete channels. Informational redundancy can be increased by measuring not only absorptiometric signals, but nephelometric too as in the device according to Fig.3. Besides, we can use sources of different wavelength: for example, red (R) and blue (B) as in Fig.4. Such alternation between colors after special processing can provide a result that will be free of sizes and shapes of scattering particles.

2.3. Turbidimeters with neural signal processing

There are a lot of factors that have an influence on measuring result in turbidimeters. To provide measurement invariance under those factors it is necessary to obtain a superabundant set of signals from a multisensor system and then use a special computational tool. One of such tools is the considered ratiometric principle, but more universal methods obtain as well. Traditionally, the well-known Least squares method is used as the mentioned tool. By means of it

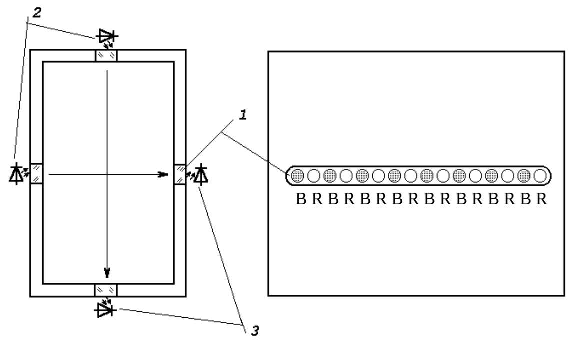

Fig. 4. A rectangle measuring cell
with arrays of sources and detectors

we can determine calibration relationships between measurands (such as voltages) and primitive physical parameters (such as turbidity, windows transparency, dispersity). Such several-dimensional relationships can be written as the following equation in vector notation:

$$\mathbf{U}=\mathbf{A}\mathbf{X}, \qquad (9)$$

where **U** and **X** are vectors of measuring and primitive parameters, **A** is an operator, linear or not. For calculating parameters of **X** we must apply the inverse operator $\mathbf{A}^{-1}$:

$$\mathbf{X}= \mathbf{A}^{-1}\mathbf{U}. \qquad (10)$$

But for all that it often happens to confront with the following difficulties:

- it is probably we can find a result having law computational stability due to bad robustness property of **A**, so even a small error in elements of **U** or **A** can lead to an immense error in finding elements of **X**;
- often it is hard to set and define parameters of **X** with acceptable accuracy ;
- the relationships (9) themselves may be rather complex, their structure and type are often unknown.

From these reasoning we come to conclusion: it is very appropriate for in-line multisensor turbidimeter signal processing to use artificial neural networks (ANN). They help to simplify considerably the problem of calibration and multidimensional signal processing.

Outputs of detectors (or some generalized parameters calculated from them) from a multisensor system may be directed to inputs of an ANN. The ANN single neuron output will represent calculated turbidity. Traditional calibration in such turbidimeters will be substituted for learning process. In that case for providing measurement invariance under some influencing factors it is not obligatory to know exactly the relationship between measurands and those factors, it is unnecessary to set exactly values of influencing factors during calibration, it is unneeded to carry out any mathematical manipulation like (10) which can be accomponied with the loss of accuracy. It will suffice to learn the ANN to ignore fluctuation of influencing factors.

For every particular project of multisensor turbidimeter there are proper ANN paradigm, configuration and learning algorithm which are more efficient than others. In case that it is more preferable to do neural processing directly at a controlled object by means of a cheap controller, Radial Basis Function (RBF) networks can be applied with much success. They are characterized by the fast learning speed, the satisfactory perfomance and the relatively small number of neurons. Generalized Regression Neural Networks (GRNN) can be learned almost instantly, but, as a rule, the hidden layer of a GRNN can have rather large number of neurons which equals to the number of cases (measurements). Generally, such ANNs require more computational resources than RBF networks. In case of using high-perfomance controllers or if a neural processing is executed by a remote computer, the Multilayer Perceptrons (MLP) may be quite acceptable. Moreover, usually it is quite enough to have only one hidden layer in the structure of such ANN. General characteristics of the MLP are its relatively slow learning speed and opportunity for obtaining high network performance. The choice of the

MLP is the most reasonable when the number of input variables and amount of sampling are large. Practically, it would be better to choose the MLP if the number of input variables is more than 4.

3. PRACTICAL EXPERIENCE

Results of testing for some described turbidimeters under condition of optical windows soiling are represented in Table 1. All turbidimeters were designed for measuring concentration of oil in water inside pipelines working under pressure up to 1,2 MPa. All of them have built-in electronic schemes and can be connected with the computer. For each type of turbidimeters the special software was applied. Calibration points from 1 to 100 mg/l were set with the special calibration equipment including the closed loop with the circulation pump and the doser. Windows soiling was emulated by overlap of 0,2-mm brown polyethylene films. Maximal errors caused by this factor are shown in Table 1.

TABLE 1. Errors caused by windows soiling

№	Brief characteristics	Illustration	Error, % F.S.
1	Moving photodiode inside sylphon. Red LED 640 nm	Fig.1	1,5
2	1 LED 850 nm, 5 photodiodes along the circumference	Fig.2	4
3	2 infrared LEDs 850 nm and 2 photodiodes. Cleaning plunger	Fig.3	1,2
4	Rectangle cell with arrays of LEDs and photodiodes. 2 wavelengths: 640, 430 nm	Fig.4	2

The author estimated different types of ANNs (RBF, GRNN, MLP) for the purpose of application in the turbidimeter 2 (Table 1) which is destinated for the measurement of oil concentration in oil-in-water emulsion. It was the aim to provide measurement invariance under condition of unstable dispersity. Usually neglect of this factor brings to errors 20-30 % F.S. The turbidimeter was built into the calibration workbench where the special mixer could change the average size of oil globules from 100 to 1 micrometer depending on mixing duration.

Values of oil concentration 80, 40, 20, 10, 5 mg/l and 0 (clear water) were set and after each change of concentration the mixing was executed during 30 min when the ratios U_0/U_1, U_0/U_2, U_0/U_3, U_0/U_4 were written into the computer memory one after another at intervals 30 s. In all we had 360 cases. As a result we had a four-variable set for an ANN inputs and a set of desirable values for an ANN output. Then various ANNs were created and tested with the help of the STATISTICA Neural Networks program package. One half of the sample data set we used as a training set and another half as a verifying set. The best results for various structures and algorithms are represented here as the averaged training errors for the verifying set (% F.S.): for GRNN - 4,44; for RBF - 4,12; for MLP with 6 neurons in the single hidden layer - 1,66. Evidently, the MLP paradigm proves to be better, so the special attention was riveted on it. Different numbers of neurons at the layer were tested. Increasing this number leads to the error decreasing (Fig. 5) only within the certain limit. It is unreasonable to do this number more than 6. Similarly, increasing the number of layers can't improve anything. Several learning algorithms were tested as well. The best result was shown by the Quick Propagation algorithm. In Fig.6 we can see the difference between the Back and the Quick Propagations.

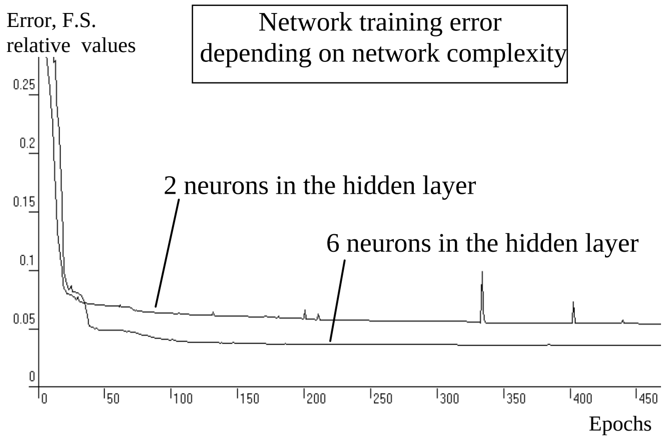

Fig.5. Training errors and network complexity

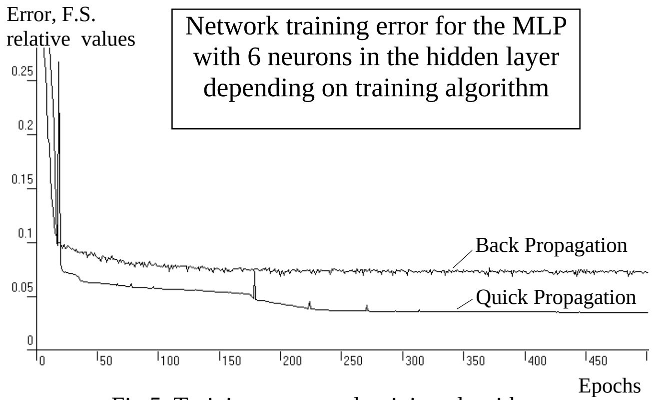

Fig.5. Training errors and training algorithms

4. CONCLUSIONS

The ratiometric signal processing is one of the basic principles for in-line turbidimeters design. Its realization may be various, and each of the considered design solutions has the own appropriate field of application. Very good results may be obtained when the ratiometric principle and neural technologies are combined.

REFERENCES

[1] V.S.Fetisov, V.T.Valeyev "Ratiometric principle of in-line turbidimeters design", *Ecological Instrument Engineering*, no.2, pp.6-7, February 2002 (in Russian).

[2] "Turbidity and Solids Content Sensor TurbiMax P CUS61", *Endress+Hauser Technical Information*, TI 228C/07/en., 2001

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