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Automatic fibre-optic sensor for oil detection

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The paper presents construction and working principles of automatic fibre-optic sensor used for distinguishing water from oil. Such a sensor can detect oil layer on water surface. The sensor consists of intensity fibre head, lift and computer measurement device with a detection block. The detection block has an implemented neural network able to distinguish a detected medium. The detection is based on the data processed from a measurement cycle. One cycle includes head submerging, submersion, emerging and emergence in the detected medium. In this way various physical phenomena are in a measured signal. The detector head is the ending of the large core polymer optical fibre. The head works on the basis of Fresnel reflection intensity.

Keywords: intensity optic sensor, oil presence, neural network, intelligent sensor

1. Introduction

The sensor consists of three functional blocks: measuring block, lift block, and optic block. The block outline is presented in Fig. 1.

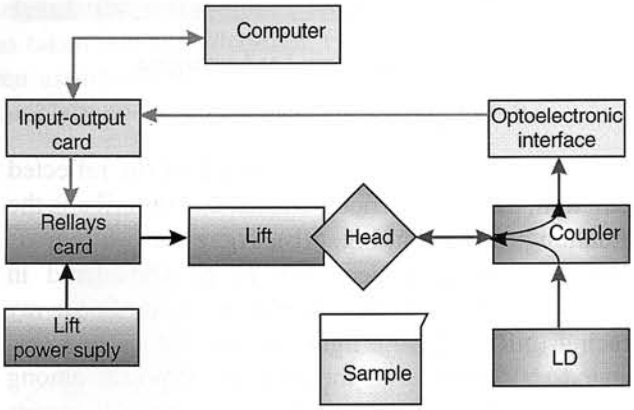

Fig. 1. Block diagram of intelligent sensor.

The measuring block is built on the basis of PC computer, input-output cards and optoelectronic interface [1]. The block's task is data acquisition and processing. It also controls the lift, equipped with the measuring head. The lift has been used to ensure repeatability of the measurement cycle. The optic block consists of fibre optic head of the sensor that is connected by coupler to the semiconductor laser and optoelectronic interface.

The head of the sensor is the ending of the large core polymer optical fibre PFM-22E-750 made by Toray that is resistant to degrading activity of oil. The coupler was done from the same type of a fibre, since its core of the diameter of 750 μm enables making a stable connection with the source of light. The laser used in sensor has 3 mW power, wavelength of 670 nm and worked with 1 kHz amplitude modulation. This modulation enables optoelectronic interface measure intensity of low-level signals [1] that is necessary because the sensor head employes Fresnel reflection phenomenon.

2. Measurement cycle

The sensor works on the basis of a measurement cycle. The cycle includes: submerging, submersion, emerging and emergence of the head from the tested liquid. The time of the light reflected from the tested medium, appearing during the measurement cycle, includes the data on the liquid type. Typical characteristics of full measurement cycles are shown in Figs. 2 and 3.

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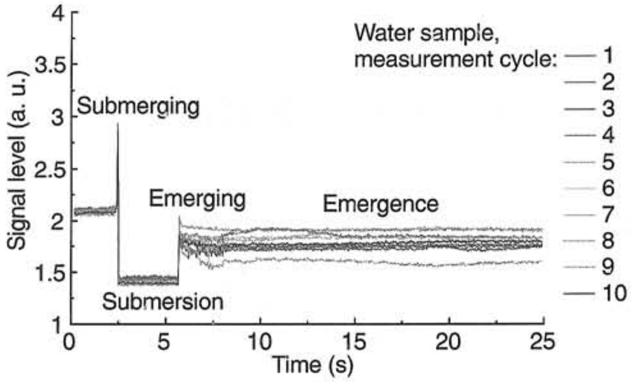

Fig. 2. Full measurement cycles in time domain for water sample.

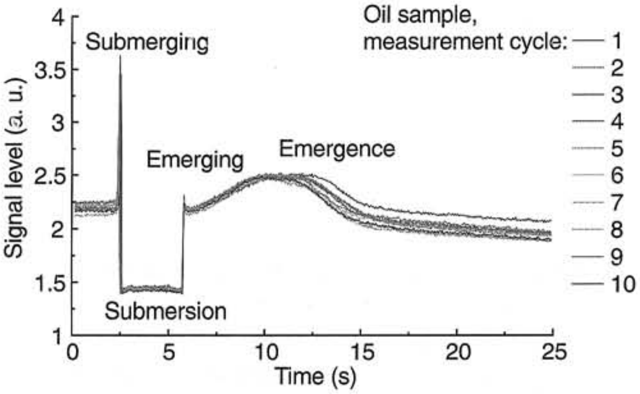

Fig. 3. Full measurement cycles in time domain for oil sample.

3. Interpretation of the measurement cycle signal

During the submerging process the head works as an approaching distance detector. In submersion the head works on the principle of Fresnel reflection phenomenon. In this case the value of the signal reflected from the liquid-core border could be assessed using the relations describing the Fresnel reflection coefficient. For the calculations was assumed that the reflection coefficient for the analysed coefficients of the refraction of the optic fibre and the liquid, and the reflection angle of the light are approximatelly constant. The relative power of the reflected signal is presented in Fig. 4. The level of the signal was assumed as 100.

The result of the above calculation is ability to distinguish the signals reflected from water and oil, on the basis of Fresnel phenomenon, during head immersion.

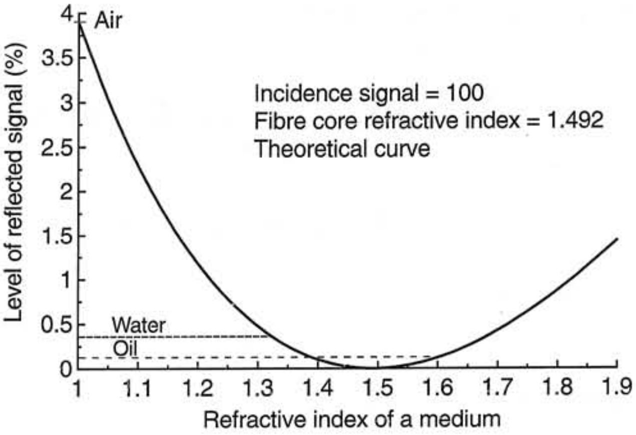

Fig. 4. Reflected signal from a submersed head.

The following state of the measuring cycle is the immersing of the head. At the moment of pulling out the ending of the head out of the liquid, the meniscus and then drops appear on it.

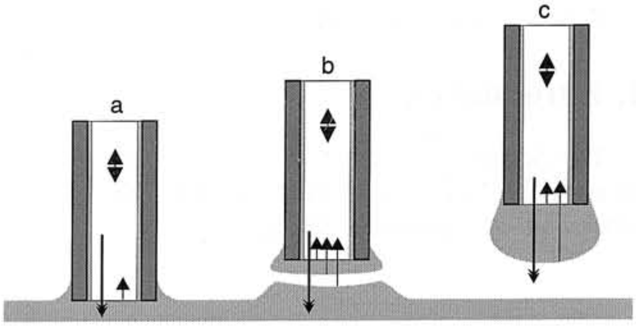

Fig. 5. Situations during sensor head emerging.

During the assessment of strength of the reflected radiation, the most difficult situation to describe is the situation presented in Fig. 5(b). There are two regions with fast changing geometry to be considered in which according to the convention of non-linear ray tracing (NRT) [2], the light rays are subjected to repeated reflections with the division of power among the media. Even in the quasi-stable state it means spreading the ray description in three media (liquid-air-liquid) to the sum of the sequences of correlated factors. Using approximation of the first words of the sequences and assuming that the media have flat borders and they are thin, we can asses the maximum reflected signal during the emergence according to the equation

$$S = S_p[r_1^2 + (1-r_1^2)^2 + (1-r_1^2)^2(1-r_2^2)^2 r_3^2],$$

where S_p is the strength of the falling signal, S is the strength of the received signal with the use of the Fresnel reflection coefficient [3]:

$$r_1 = \frac{n_0 - n_r}{n_0 + n_r},$$

$$r_2 = \frac{n_0 - n_p}{n_0 + n_p},$$

$$r_3 = r_2$$

In the above equations n_o is the oil refraction coefficient, n_p is the air refraction coefficient, and n_r is the optic fibre core refraction coefficient.

The assessed maximum level of the reflected signal, for oil with $n_0 = 1.6$, and for the core with $n_r = 1.492$, equals 10,19% of the initial value. For water it equals 4.08%.

During further emerging, on the endings of the optic fibre cable the drops or thin layers of liquid are formed. In this case the signal value was established using numerical simulation method, according to the NRT principles. To achieve it, two-dimensional model of the head ending was constructed. It has been assumed the ending of optic fibre ending core was the source of light. In its area the points and the angles of the rays leaving the core were chosen randomly and according to the uniform distribution its routes were analysed. The distribution of power among the media was taken into consideration. For simplification it has been assumed that the front of the drop is flat. The examplary course of the ray is shown in Fig. 6.

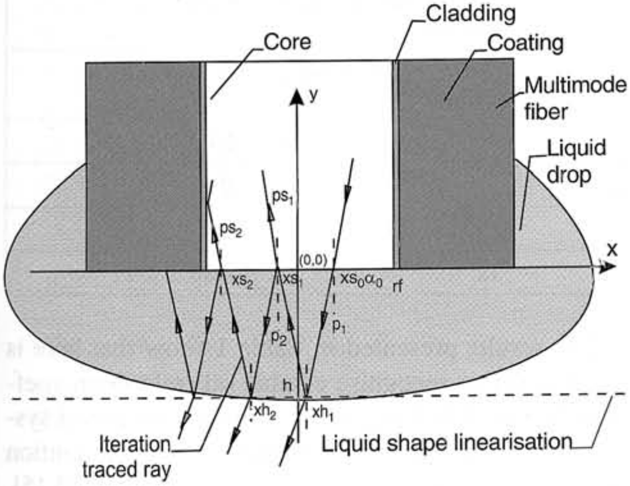

Fig. 6. Sample traced a ray path in liquid.

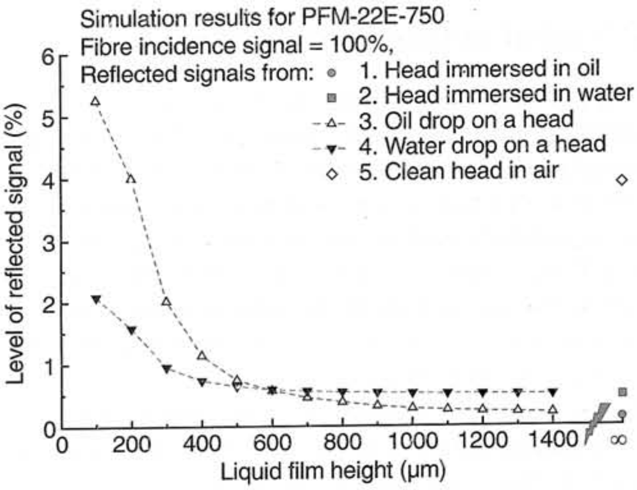

Fig. 7. Slow variation and constant reflected signals forthcoming from a head.

The obtained results of simulation for the drop of water ($n_w = 1.33$) and oil ($n_0 = 1.6$) are presented in Fig. 7.

From the data presented in Fig. 7 we can see that, for expected liquid film heights (lower that 500 µm), the signal level after the emergence coming from the oil shall be higher that the signal from water. It will also be characterised by significant changes of level during dripping and forming of the drops, since those processes can be interpreted as the changes in drop's height.

On the basis of the presented facts we can interpret the signals appearing in Figs. 2 and 3. During the submersion process of the head there appears a signal reflected from the liquid surface. The reflection from the water surface is much smaller than from the oil. It results from the differences between reflection coefficients of water-air and oil-air media. Next, in submersion the decrease in the signal value for the water and oil samples is similar due to low level of the measured signal and small differences between reflection coefficients of oil, water and the core of the fibre optic cable (oil 1.4, water 1.33, the core 1.491). During emergence process of the head from oil the measured characteristics present the slow process of formation of a thick drop (an increase and a decrease in the signal). During the emergence of the head from water the signal is constant because drop forming does not proceed. The signal level is lower than the input signal (reflected from the air), it proves the existence of the water layer on the head front. The signal level after the emergence of the head from water is lower than the signal received after the emergence from oil, which is in accordance with the calculations.

4. Neural network application

It has to be noticed that within one media the time course of the consecutive measurement cycles, presented in Figs. 2 and 3 are well repeatable. What comes from this fact is, that the characteristic features of the particular signal or the measurement cycle, collected into a model, can be used for recognition of the media. For recognition of the data models the neural network can be used. Its use for the recognition of eatable oil-water media seems especially reasonable due to the small differences of the signals between those media, obtained in the case of static immersed head. As the signal data model the following were assumed:

- starting level,
- maximum level during the submersion process,
- level in the submersion,
- levels during the emergence process determined by the period of the measurement for: 7.5, 10.0, 12.5, 15.0, 25.0 seconds, as moving average: 1 second of averaging with 3 measurement points,
- average value and standard deviation of the signal during the emergence process.

Because of the assumption that the two media have to be differentiated, the network with one output was designed. The output signal was assumed within the range 0–1. The signal close to 0 informs about the network input data model signal for water and 1 stands for data model of eatable oil. All other liquids were classified outside those values. For the learning process the multilayer perception [4] network with the following parameters was selected:

- number of layers – 4,
- input layer with 10 elements and 10 inputs, for whose the signals, described above are given with the linear transfer function,
- first hidden layer, 4 elements, sigmoid transfer function,
- second hidden layer, 3 elements, sigmoid transfer function,
- output layer, 1 element, sigmoid transfer function.

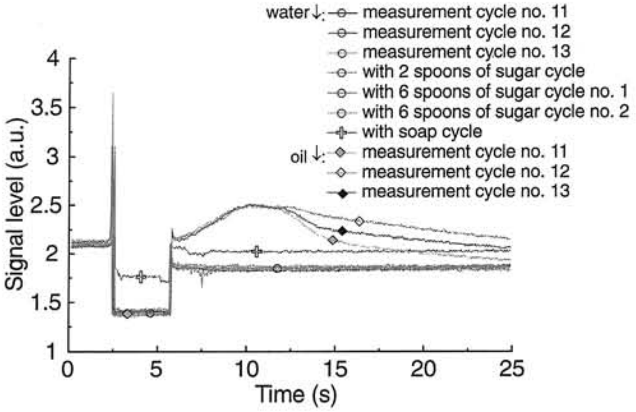

Fig. 8. Samples of oil and water used for neural network testing.

The learning process of the network was done for the data presented in Figs. 2 and 3, which means 20 data models. The test data models were not used. The learning error for 1000 iterations of the "back propagation" algorithm was 0.0121%. It means that the network parameters were well selected and the learning process of the desired features occurred. The network, taught in the system of oil detection, was tested on oil and water discrimination. To achieve that the additional following data were gathered: water, water with sugar (normal sweetening 2 spoons per glass and "turbo" sweetening – 6 spoons per glass), water with soap, and other samples of oil. The data is presented in Fig. 8.

After the processing of data into data models and giving them into the taught neural network, the obtained results were presented in Table 1.

Table 1. Results of neural network recognition.

Kind of liquid	Sample	Answer	Assumed answer
Water	11	–0.01	0
	12	–0.01	0
	13	0.01	0
	with 2 spoons of sugar	–0.01	
	with 6 spoons of sugar (sample 1)	–0.01	
	with 6 spoons of sugar (sample 2)	0	
	with soap	0.02	
Oil	11	0.97	1
	12	0.86	1
	13	0.86	1

The results presented in Table 1 show that here is no difficulty to recognise eatable oil (refraction coefficient about 1.4) from water using the proposed system. To achieve that it is enough to set the recognition limit for water at 0 ±0.02, and for oil at 1 ±0.15 [5]. The liquids that give the signal outside that limit should be treated as others. For the data presented in the Table 1, water with soap should be treated as other liquid.

5. Conclusions

In the presented sensor, the taught neural network distinguishes eatable oil and clean water. The neural network, due to the use of additional information about the interaction liquid-optic-fibre, appearing during the submerging, submersion and emergence processes, distinguishes more precisely and more repeatable the tested medium than an intmerse sensor that uses only the differences of the signal at the submersion. For the presented sensor this results in relatively low-power laser diode requirement comprising with the intmerse sensor.

The neural network application in detection system effects also in sensor flexibility that can be easily adapted for other liquids distinction, for example, water and alcohol. When the network will be neglected, the other way of time signal recognition should be implemented. For the presented case the signal changes in head, emergence state could be used. This procedure is not excellent: clean water and water with soap give constant signals, so the level of signals should be also used, and for more precise detection also signal levels in emergence. This way we can tend the quite complicated dedicated detection system.

The following advantage of this system is the extremely simple construction of the sensor head and its ability of regeneration by cutting off the ending of the optic fibre cable.

Another advantage is the big system's resistibility towards the user, since the mechanical manipulations necessary for proper functioning of the system are not complicated: wiping of the ending of the thick optic fibre cable (with the diameter of the coating = 2.2 mm) with a blotting – paper between the measurements and pressing the start button to commence the measurement process.

The total advantage of presented sensor is the possibility of its implementation to monitoring of water surface pollution by oil and oily liquids.

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