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New approach for increasing the precision of TDR analysis of multilayer environments

The authors propose the solution allowing to determine the structure and the layers parameters of the multiphase liquid in real-time mode and thereby to increase the measurement precision. The method is based on using the periodic controllable loads in the measuring probe construction, which can change their own parameters at the required time moment. In the paper a description of the mathematic model of the proposed solution is presented; an algorithm for determination of the layers parameters of the multiphase liquid is proposed; the calculation example of the model multiphase liquid parameters using the proposed algorithm is shown. Also the comparison of the precision of the proposed and standard approaches is presented.

Keywords: level measurement, multiphase liquid, TDR, method, measuring probe, controllable loads, parameters measurement.
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One of the standard processes of modern industry is measurement of liquid levels in tanks. In spite of the availability of a variety of methods and techniques for implementation of this procedure, their application efficiency and measurement precision are often related to the parameters of measuring liquids and their change under the influence of external factors. One of the actual tasks is the analysis of a multilayer medium, which is the combination of several liquids with different properties. An example is the monitoring task of layer-by-layer composition of liquids at the stage of oil-product clearing requiring the determination of the following levels: the oil, the bottom water and the emulsion layer.

One of the promising methods for solving this task is the time domain reflectometry (TDR) method, which was initially applied for the diagnostics of cable lines [1]. The method is as follows: the investigated object is affected by a video pulse or step function. Analyzing the object response to the test signal, its properties are determined.

In the 1960s the TDR method was first applied to determine the level of the single liquid [2]. In [3] the application of the method for measuring of the multiphase liquid's levels (fuel oil and seawater) is described. The article [4] shows the detailed description of physical principles of the liquid level measurement using the TDR method. In addition, in this article the comparison with the alternative methods is presented. Numerous papers [5–8] describing the practical implementation of the TDR method for liquids' level measurement are known.

The restriction for the existing solutions is that priori information about the parameters of the multiphase liquid for the accurate determination of its levels is used. Consideration of these parameters is performed either on the basis of reference data or as a result of the calibration procedure during the mounting of the measurement system. In the latter case the highest accuracy is achieved.

However, in practice the liquids' properties are not stationary and depend on external conditions and can be changed during the measurement. The interface between adjacent layers is often an emulsion, whose parameters are quite difficult to predict. A high temperature of the measured liquids leads to intense evaporation of the upper layers and the change of the air layer properties. This is rarely taken into account when the method is used.

Problem definition

It may be concluded that the values of the predefined parameters of a liquid may be true only in a limited time interval. To improve the accuracy of the TDR analysis of multiphase liquids, it is necessary to dynamically determine the parameters of each layer during the measurement.

Thus, a relevant task is to find a method for determining the multiphase liquid's parameters. The method must allow getting the properties of the inner layers of this liquid in real time.

Theory

One of the ways to improve the accuracy of level sensors based on the TDR is shown in the patents [9, 10]. The authors offer to use the periodical discontinuities in the probe design for the calibration of signal propagation speed in the investigated environments using the delays of the signals reflected from these discontinuities. The disadvantage of such solution is the attenuation of the energy of the useful signal on this discontinuities and complication of the reflectogram due to the presence of a lot of reflections between them.

Based on this calibration method, we offer the following solution of the problem: to use the controllable loads with the known parameters in the probe design. It allows to realize two operating modes of the measuring probe: the calibration mode in which the condition of the controllable loads is successively changed and the parameters of the investigated environments are determined, and the measurement mode in which the controllable loads have no effect on the signal propagation in the probe, or distortion caused by their presence is not significant.

1. Mathematical model of the proposed solution

In Fig. 1 an example of the measuring probe with the controllable loads is shown.

For simplicity the case in which each layer of the measuring liquid contains at least one controllable load in the measuring probe will be considered. The equivalent circuit diagram of such measuring probe represents the cascading segments of the transmission lines $L_{i,j}$ and the controllable loads, which represent the lumped obstacle Z_k.

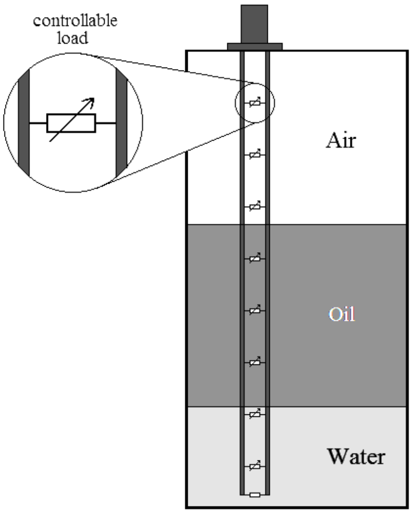

Fig.1. Example of the measuring probe with controllable loads

The model of such probe with the controllable loads can be described by the method of classic transmission matrix. The full transmission matrix of the measuring probe AP is equal to the product of the matrices AL, each of which complies with the segment of the measuring probe in a layer of the modeled liquid:

$$AP = \prod_{i=1}^{N} AL_i \ ,$$

where i – the index of the layer; N – the number of the modeling layers.

The equation of the transmission matrix of the measuring probe segment AL_i can be written as:

$$AL_i = \left(\prod_{j=1}^{M} A_{i,j} \cdot AZ_{i,j}\right) \cdot A_{i,M_i+1} \ ,$$

where j – the index of the controllable load in i-th layer; M_i – the number of the controllable loads in i-th layer; $A_{i,j}$ – the transmission matrix of the measuring probe segment; $AZ_{i,j}$ – the transmission matrix of the controllable load.

The transmission matrix of the measuring probe segments $L_{i,j}$ can be written as:

$$A_{i,j} = \begin{bmatrix} ch\left(\gamma_i \cdot l_{i,j}\right) & \rho_i \cdot sh\left(\gamma_i \cdot l_{i,j}\right) \\ \frac{1}{\rho_i} \cdot sh\left(\gamma_i \cdot l_{i,j}\right) & ch\left(\gamma_i \cdot l_{i,j}\right) \end{bmatrix},$$

where $l_{i,j}$ – the length of the segment $L_{i,j}$; ρ_i – the impedance of the transmission line segment; $\gamma_{i,}$ – the propagation coefficient equal to:

$$\gamma = \alpha + j\beta \ .$$

In the simplest case, the controllable load can be written as transmission matrix of a quadripole:

$$AZ_k = \begin{bmatrix} 1 & 0 \\ 1/Zp_k & 1 \end{bmatrix},$$

where Zp_k – the impedance of the controllable load Z_k.

Voltage on the input of the measuring probe immersed in a multiphase liquid is determined as

$$u_{in}(t) = F^{-1}\left(E(f) \frac{Z_{in}(f)}{Z_{in}(f) + Z_g} \right),$$

where $E(f)$ – the spectrum of the test signal; Z_g – the output resistance of the generator; F^{-1} – inverse Fourier transform operator; $Z_{in}(f)$ – the frequency response of complex input resistance of the probe.

The frequency response of complex input resistance of the probe can be define by formula

$$Z_{in}(f) = \frac{AP_{0,0}(f) \cdot Z_l + AP_{0,1}(f)}{AP_{1,0}(f) \cdot Z_l + AP_{1,1}(f)} \ ,$$

where Z_l – the load resistance on the measuring probe output.

The main function of the controllable loads Z_k is to perform the mode of full or partial reflection of the test signal for determination of the layer parameters of the liquid under investigation, which are calculated based on the known distance l_k^* from the measuring probe entrance to the controllable load.

2. Algorithm of determining the structure and the parameters of a multiphase liquid

The algorithm of determining the layer parameters of a multiphase liquid contains the following steps:

1. Formation of the vector of reflectograms.

The sequence of the calculation of the measuring probe reflectograms for the definite set of the controllable loads states is conducted. The reflectogram vector U_k is formed, where k – the number of a controllable load providing the mode of the full or partial reflection of the test signal. Index $k = 0$ corresponds to the mode in which all controllable loads have off-state.

2. Definition of the response array.

Based on the received reflectogram, the two arrays are formed: R – the array containing the information about the responses reflected from the phase boundaries and the end of the measuring probe. R^* – the array containing the information about the responses reflected from the controllable loads.

The elements of the vectors $R^{<1>}$, $R^{*<1>}$ are response delays relative to the test signal, and the elements of the vectors $R^{<2>}$, $R^{*<2>}$ are the amplitudes of the responses.

During formation of the array R, to avoid the parasitic responses caused by signals multiple reflections from the phase boundaries, the signal selection algorithm is applied [11].

The value of the element R_0 complies with test signal response.

To form the array R^*, differences of reflectograms $\Delta U(t)$ determined in the step 1 are calculated:

$$\Delta U_k(t) = U_k(t) - U_0(t) \ ,$$

where $k \in [1, K]$; K – the number of the controllable loads in the measuring probe.

The values of the elements R_k^* comply with delays and amplitudes of the first responses on each difference reflectograms $\Delta U(t)_k$.

3. Definition of the controllable loads belonging.

Belonging of the controllable loads to the analyzed liquid layers are defined. For that, element-by-element comparison of the delay vectors $R^{*<1>}$ и $R^{<1>}$ is provided. For each element R_k^*, the appropriate layer index i, in which the controllable load is located and the number of the controllable load j in the i-th layer are provided. As a result, each element of the array R^* and the vector l^* may be characterized by indexes i and j, writing them in the form of $R_{i,j}^*$ and $l_{i,j}^*$.

4. Definition of the layers parameters of the multiphase liquid.

The layers' parameters of the measured liquid ε_i and α_i are determined for each layer in the following sequence:

a) based on the parameter of the responses reflected from the controllable loads, the average value of the propagation velocity υ_i in i-th layer is calculated:

$$\upsilon_i = \frac{1}{M_i}\sum_j \frac{2\cdot\left(l_{i,j}^* - \sum_{n=1}^{i-1} l_n\right)}{R_{i,j}^{*<1>} - R_{i-1}^{<1>}}. \qquad (1)$$

b) the dielectric constant and the length of the layer are determined:

$$\varepsilon_i = \left(\frac{c}{\upsilon_i}\right)^2, \qquad (2)$$

$$l_i = \frac{\upsilon_i \cdot \left(R_i^{<1>} - R_{i-1}^{<1>}\right)}{2}, \qquad (3)$$

where c – the speed of light.

c) the average value of the attenuation coefficient α_i [N] in i-th layer is calculated:

$$\alpha_i = \frac{1}{M_i}\sum_j \frac{\ln\left(\left|\dfrac{R_0^{<2>}\cdot\prod_{n=1}^{i-1}\left((1-\Gamma_n^2)\cdot e^{-2\cdot l_n\cdot\alpha_n}\right)}{R_{i,j}^{*<2>}}\right|\right)}{2\cdot\left(l_{i,j}^* - \sum_{n=1}^{i-1} l_n\right)}, \qquad (4)$$

where Γ_i – reflection coefficient from i-th layer determined by the formula:

$$\Gamma_i = \frac{R_i^{<2>}}{R_0^{<2>}\cdot\prod_{n=1}^{i-1}\left((1-\Gamma_n^2)\cdot e^{-2\cdot l_n\cdot\alpha_n}\right)\cdot e^{-2\cdot l_i\cdot\alpha_i}}. \qquad (5)$$

Modeling

The developed algorithm based on using the periodic controllable loads in the measuring probe construction has been tested on the mathematic model. The parameters of the model liquid are shown in Table 1.

The model of the measuring probe contained three controllable loads (K = 3), which are located in the different layers of the multiphase liquid and provide the mode of full reflection in the on-state. The distances from the measuring probe entrance to the controllable loads are the following: l_1^* = 0,375 m; l_2^* = 0,75 m; l_3^* = 1,125 m.

Table 1

Multiphase liquid parameters

Layer number	Dielectric constant ε	Losses α, dB/m	Layer length, l, m
1	1	0,5	0,5
2	3	1	0,5
3	80	2	0,5

To determine the layer parameters of the multiphase liquid, the described algorithm is applied. At the first stage the reflectograms $U_k(t)$ in the modes k = 0 (Fig. 2) and k = 1, 2, 3 (Fig. 3) are calculated and the response arrays R and R^* are formed

$$R = \begin{bmatrix} t_0 & A_0 \\ d_1 = t_1 - t_0 & A_1 \\ d_2 = t_2 - t_0 & A_2 \\ d_3 = t_3 - t_0 & A_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 3{,}33\cdot10^{-9} & -0{,}25 \\ 9{,}1\cdot10^{-9} & -0{,}53 \\ 3{,}89\cdot10^{-8} & -0{,}34 \end{bmatrix}.$$

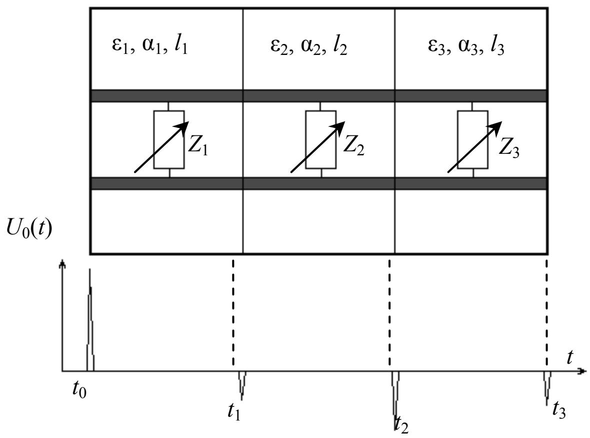

Fig. 2. Forming the reflectogram $U_0(t)$ in the mode k = 0

$$R^* = \begin{bmatrix} d_1^* = t_1^* - t_0^* & A_1^* \\ d_2^* = t_2^* - t_0^* & A_2^* \\ d_3^* = t_3^* - t_0^* & A_3^* \end{bmatrix} = \begin{bmatrix} 2{,}5\cdot10^{-9} & -0{,}96 \\ 6{,}22\cdot10^{-9} & -0{,}83 \\ 1{,}66\cdot10^{-8} & -0{,}4 \end{bmatrix}.$$

After forming the arrays R and R^*, belonging of the controllable loads to the analyzed liquid layers is defined by comparison of the vectors elements $R^{*<1>}$ and $R^{<1>}$:

Z_1: $d_1^* < d_1$ – belongs to the first layer, $i = 1$, $j = 1$;

Z_2: $d_1 < d_2^* < d_2$ – belongs to the second layer, $i = 2$, $j = 1$;

Z_3: $d_2 < d_3^* < d_3$ – belongs to the third layer, $i = 3$, $j = 1$.

In Table 2 the parameters A^*, d^*, l^* corresponding to the controllable loads are represented in the form of a table.

Finally, the layer parameters of the multiphase liquid are defined in sequence by formulas (1)–(5). Calculation results are shown in Table 3.

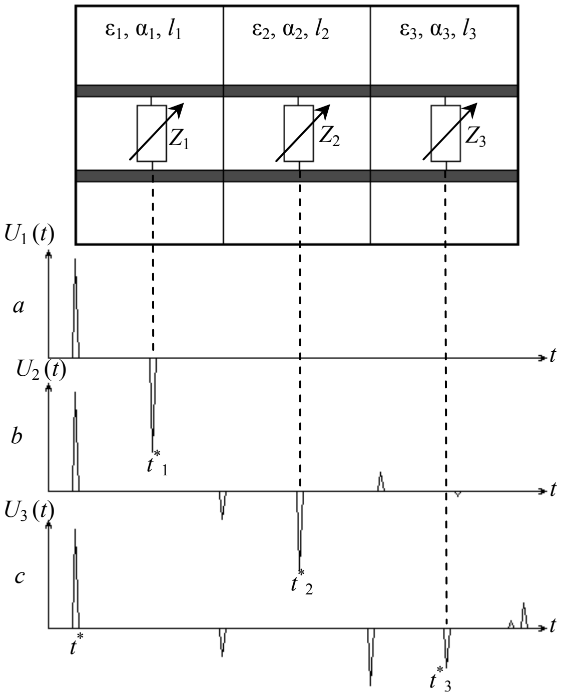

Fig. 3. Forming the reflectograms $U_1(t) - U_3(t)$, where
a – the reflectogram in the mode $k = 1$ ($Z_1 = 0$);
b – the reflectogram in the mode $k = 2$ ($Z_2 = 0$);
c – the reflectogram in the mode $k = 3$ ($Z_3 = 0$).

Table 2

Controllable loads parameters

i	j	$R^*_{i,j}$		Distance to the controllable load $l^*_{i,j}$, m
		Response delay $d_{i,j}$, s	Response amplitude $A_{i,j}$, V	
1	1	$2{,}5\cdot10^{-9}$	–0,96	0,375
2	1	$6{,}22\cdot10^{-9}$	–0,83	0,75
3	1	$1{,}66\cdot10^{-8}$	–0,4	1,125

Table 3

Calculated parameters of the multiphase liquid layers

layer number	Layer length l_i, m	Losses α_i, dB/m	Impedance ρ_i, Ohm	Dielectric constant ε	Propagation velocity υ_i, m/s
1	0,5	0,5	50	1	$3\cdot10^8$
2	0,5	1	28,86	3	$1{,}73\cdot10^8$
3	0,5	2	5,59	80	$3{,}36\cdot10^7$

Comparison of the standard approach and the new solution

For the evaluation of efficiency of the new approach it was performed the modeling of the measurement of the multiphase liquid parameters using the standard and new measurement approaches. The key difference between the approaches is method for evaluation of the environment dielectric constant: in the standard approach the reference data is used; in the proposed solution the measurement of the environment parameters is performed in calibration mode.

The parameters of the model multiphase environment and reference data about the dielectric constant of the layers are presented in the Table 4.

Table 4

Multiphase liquid parameters

Layer number	Dielectric constant ε	Reference dielectric constant ε	Losses α, dB/m	Layer length l, m
1	1,05	1	0,5	0,3
2	2,3	2,1	1	0,5
3	70	80	2	0,5

The measuring probe which is realized the new approach contained six controllable loads ($K = 6$). The positions of the loads in the probe are shown in the Table 5. The probe length is equal to height of the tank.

Table 5

Localization of the controllable loads in the probe design

Controllable load number	The distance to the controllable load
1	0,186
2	0,371
3	0,557
4	0,743
5	0,929
6	1,114

In the modeling the noise of generator and receiver are taken into consideration. The noises parameters are following: normal law of distribution, RMS-noise of the generator – 1 mV, RMS-noise of the receiver – 600 µV. Also in the model the quantization procedure with resolution 16 bit was added.

The calculation result of the length of the layers for both approaches is presented in the Table 6. Also in the table the relative measurement errors are shown.

Table 6

Calculated length of multiphase liquid layers

Layer number	Standard approach		Proposed approach	
	Layer length l, m	Relative error δ, %	Layer length l, m	Relative error δ, %
1	0,307	2,333	0,299	0,045
2	0,523	4,6	0,5003	0,062
3	0,468	6,4	0,499	0,102

The presented calculation results show that the proposed method has higher accuracy compared to standard method. The higher accuracy of the proposed solution pre-conditioned by the ability to measure of the parameters of investigated environment during the measurement procedure.

Conclusion

To determine the levels of multiphase liquids using TDR method with high precision, it is necessary to know the structure of the multiphase liquid and parameters of its layers. Taking into consideration the fact that the parameters of the measured liquid are often not stationary and depend on the environment condition, the procedure of parameters determination, at the best case, must be provided at the moment of the levels measurement.

In the paper, we propose a solution allowing to determine the structure and the layers parameters of the multiphase liquid in real-time mode and thereby to in-

crease the measurement precision. The method is based on using the periodic controllable loads in the measuring probe construction, which can change their own parameters at the required time moment. In the paper a description of the mathematic model of the proposed solution is presented; the algorithm for determination of the layers parameters of the multiphase liquid is proposed; the calculation example of the model multiphase liquid parameters using the proposed algorithm is shown; the comparison with standard approach is presented. The presented calculation result shows high efficiency of the proposed method, so using the controllable loads in the measuring probe construction is a perspective solution for the task of extracting the multiphase liquids parameters.

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Тренкаль Е.И., Лощилов А.Г.
Новый метод повышения точности TDR-анализа многослойных сред

Предложено решение, позволяющее в режиме реального времени определять структуру и параметры слоев многофазной жидкости, тем самым повысить точность измерения. Метод основан на использовании в конструкции измерительного зонда управляемых нагрузок, способных изменять свои параметры в необходимый момент времени. В работе представлено описание математической модели предложенного решения; предложен алгоритм определения параметров слоев многофазной жидкости; показан пример расчета параметров модельной многофазной жидкости по описанному алгоритму. Также представлено сравнение точности предлагаемого решения и классического подхода измерения.

Ключевые слова: измерение уровня, многофазная жидкость, TDR, способ, измерительный зонд, управляемые нагрузки, измерение параметров.

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