RC quasi-distributed sensor with tree-like structure adaptable for physical fields measurement

I.D. Shafigullin[*], E.S. Denisov

Kazan National Research Technical University named author A.N. Tupolev – KAI

*ilnaz_shafigullin@mail.ru

Abstract

The paper presents a new conception of quasi-distributed sensor for simultaneous measurement of several physical fields and the results of an experimental study of this sensor. A distinctive feature of the sensor defined by the sensitive *RC* elements connected in the original tree-like structure. The proposed is the structure of the sensor and measurement system as well as corresponding measurement algorithm. The high accuracy demonstrated by the sensor's prototype gives possibility to effective use the proposed sensors in many technical and scientific applications.

Keywords: quasi-distributed sensor, tree-like structure, sensitive RC elements, physical fields measurements

Introduction

Most scientific and technical problems involve measuring physical quantities. Traditionally discrete point sensors which allow obtaining local or averaged values of the measured physical quantity are used to solve this case. However, when the problem of measuring distributed physical fields arises, specialized measuring instruments are required. Such instruments can be obtained based on a large number of classical discrete point sensors. However, there are technical difficulties associated with the requirement for a large number of connecting wires and measuring channels, which leads to increased cost, weight, and size of equipment. These limitations could be overcame by using a conception of distributed [1 – 3] or quasi-distributed [4 – 6] and their technical implementation.

It is known [7, 8] a tree-like structure for connecting resistive sensitive elements in a quasi-distributed resistive sensor. A distinctive feature of such a connection is that individual resistive sensitive elements are connected in a tree-like structure, in which only the external sensor terminals are available for measurements. Due to the tree-like structure, it is possible to separate paths for probing and measuring currents. In this case, the influence of parasitic resistances on the measurement results is excluded, and the method of measuring the resistances of individual sensitive elements is obtained similar to the four-wire measurement circuit. However, the main limitation of such a sensor is the possibility to measure just on physical quantity. To overcome this limitation, a new quasi-distributed *RC* sensor with a tree-like structure is proposed and the possibilities of simultaneous measurement of two physical quantities are considered.

Quasi-distributed *RC* sensor

Fig. 1 shows the concept of physical field measurements based on quasi-distributed resistive sensors with tree-like structures [7, 8] and the corresponding technique for determining the parameters of individual sensor elements. The example of a quasi-distributed resistive sensor (Fig. 1) comprises 15 sensitive elements and has nine external terminals (*T*0-*T*8) for connecting a probing current source and measuring equipment.

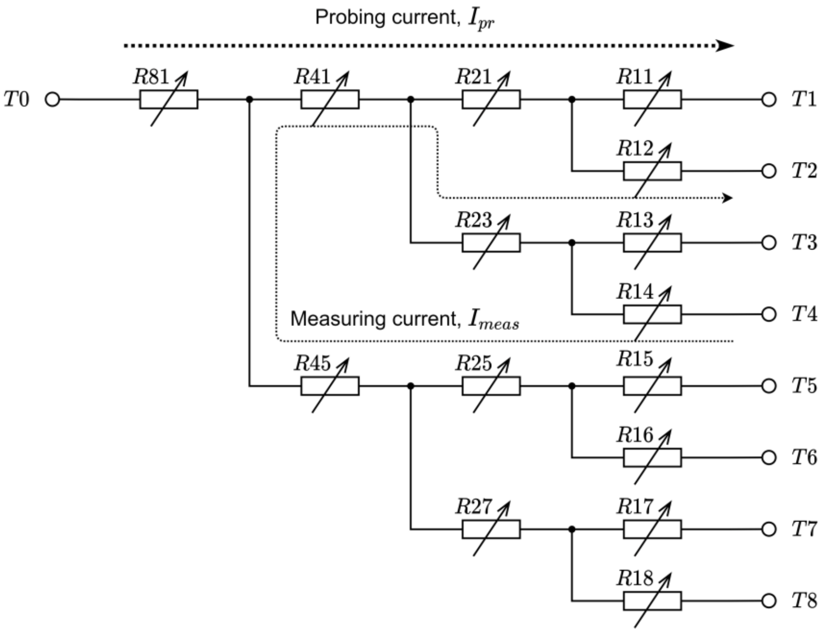


Fig. 1. Quasi-distributed resistive sensor with tree-like structure

The tree-like structure provides separated paths for probing and measuring currents. For example, Fig. 1 demonstrates the distribution of the currents for measuring the resistance of sensitive element *R*41. In this case, the current probing signal source is connected between the terminals *T*0 and *T*1, while the voltage-measuring device is linked to the terminals *T*5 and *T*3. Based on the known magnitude of probing current and the measured voltage across the considered resistive sensitive element it is possible to determine the required electrical resistance according to Ohm's law:

$$R41 = \frac{U_{T5-T3}}{I_{pr}}, \qquad (1)$$

where U_{T5-T3} is the voltage between terminals *T*5 и *T*3; I_{pr} is the probing current. The resistive sensitive elements *R*81, *R*21, and *R*11 do not affect the measurement results, since they do not change the value of the probing current. The influence of the sensitive elements *R*15, *R*25, *R*45, *R*23, and *R*13 can be neglected provided that the measuring current is small enough $I_{meas} << I_{\mathrm{pr}}$. The last condition can be met with voltage measuring devices with high input impedances. It is possible to scan all resistive sensitive elements of such quasi-distributed resistive sensor by appropriate switching of the probing signal source and the measuring device. The description of corresponding measurement procedure is described in [7, 8].

Each sensitive element of a resistive sensor is sensitive to only one physical quantity, however, it is often necessary to measure the spatial distribution of several interconnected physical fields. For example, the fields of mechanical stresses and deformations in building structures, the distribution of temperatures and current densities over the membrane surface of hydrogen fuel cells, determining the place and force of pressing in touch panels, etc. The use of more complex sensitive elements within tree-like quasi-distributed sensors can provide the required functionality.

For this purpose, it is proposed to use sensitive *RC* elements based on the parallel connection of resistive *R* and capacitive *C* sensitive elements. The resistances and capacitances of these elements can be sensitive to two different physical fields. A quasi-distributed sensor composed of such elements and connected in a tree-like structure will be called a quasi-distributed *RC* sensor with a tree-like structure.

Fig. 2 shows an example of a quasi-distributed *RC* sensor with a tree-like structure comprising 15 sensitive *RC* elements.

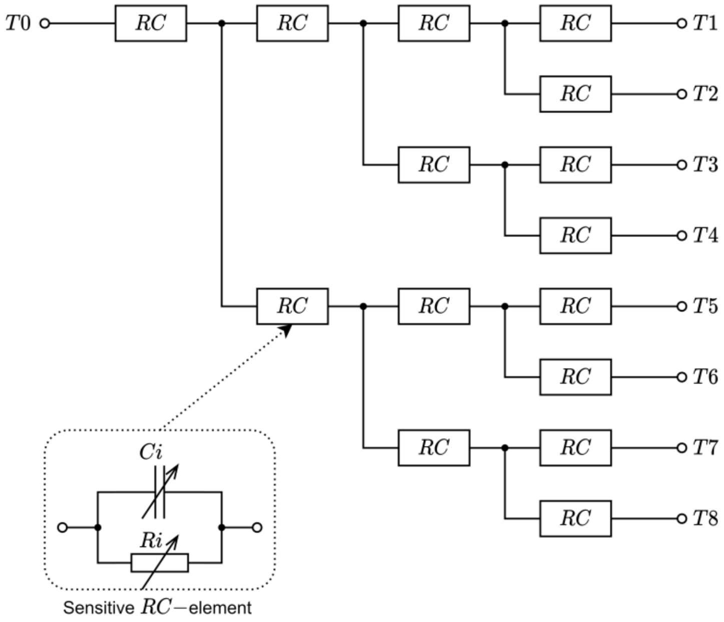


Fig. 2. A quasi-distributed *RC* sensor with a tree-like structure

The method for measuring the resistance *R* of a resistive sensing element included in the *RC* element is similar to the method described above for a quasi-distributed resistive sensor with a tree-like structure. However, the measurements had to be carried out in a steady state after the end of transient processes associated with the charge/discharge processes in capacitive elements.

The evaluation of sensitive element capacitance *C* can be implemented based on *RC* element time constant estimation. Obviously that the time constant can be determined during both processes charge and discharge. However, it is experimentally established that charge processes are under the strong influence of output impedance of probing current source. Therefore it is recommended to use an analysis of the discharge relaxation caused by probing current interruption. In this case, the time constant of the relaxation process is described by the following equation:

$$\tau = RC. \tag{2}$$

Since the resistance *R* is known from the previous stage of the measurement procedure, the capacitance *C* can be estimated as:

$$C = \frac{\tau}{R}. \tag{3}$$

The proposed measurement technique can be used to determine the parameters of quasi-static physical fields, the parameters of which stay constant during measurement procedures. To measure physical fields with lower characteristic time, it is possible to decrease the time constant of sensitive elements and faster analog multiplexers.

The typical structure of the measuring system based on tree-like quasi-distributed *RC* sensor

Fig. 3 shows a typical block diagram of a system for measuring physical fields using a quasi-distributed *RC* sensor with a tree-like structure.

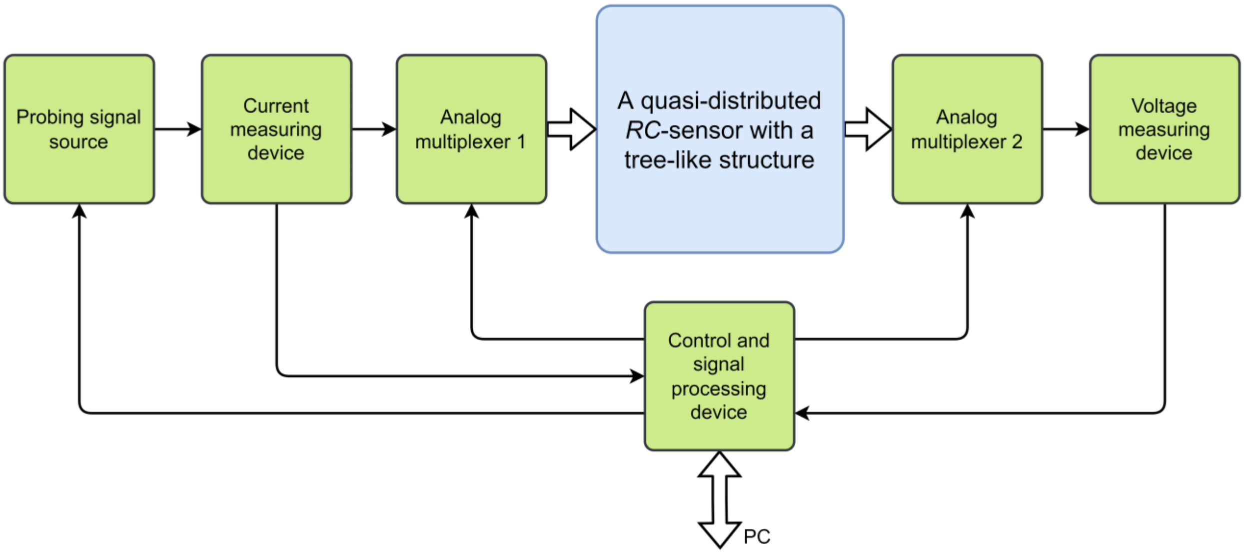


Fig. 3. Block diagram of a system for measuring physical fields using tree-like quasi-distributed *RC* sensor

The algorithm of the system operation is as follows. During the first stage of the measurement procedure, the sensitive *RC* element under consideration is selected. Using analog multiplexer 1, the probing signal source is connected to the sensor in such a manner to make the probing current flow through the considering *RC* element. The current measuring device measures the real value of I_{pr}. In the steady state after the termination of the transient process, the amplitudes of the probing current and the voltage across the considering sensitive *RC* element estimate the resistance of the sensitive element according to (1). In this case, the voltage measuring device is connected to terminals of the sensor by analog multiplexer 2 in such a way that paths of measuring and probing currents have just one common element, namely, the considering *RC* element. During the second stage of the measurement procedure, the probing signal source is disconnected from the considering sensitive element triggering the transient discharge process. The voltage measuring device meters the *RC* element voltage behavior in time. The

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 24 October 2022 doi:10.20944/preprints202210.0367.v1

control and data processing device estimates the time constant τ and calculates the capacitance C of the considering sensitive RC element according to (3).

Results and discussion

Based on the block diagram shown in Fig. 3, a measuring setup was implemented with the equipment of National Instruments, Inc. NI PXI-4110 module with a built-in current measuring device that performs the function of probing signal source. NI PXI-5922 module with a maximum sampling rate of 15 MHz measures voltage between terminals of quasi-distributed RC sensor. Analog multiplexers 74HC4051 commutate of probing signal source and voltage measuring device. STM32F411 microcontroller based on commands from the main controller NI PXIe-8840 controls the analog multiplexers.

The experimental model of a quasi-distributed RC sensor consists of 15 RC elements. Resistors with a nominal value of 100 Ohm and with an accuracy of 5% are used as the model of sensitive RC elements resistive part, which corresponds to the typical value of platinum thermal resistance. Capacitors with a nominal value of 470 nF and accuracy of 5% model the capacitive part of sensitive RC elements. Thus, the time constant of the RC element is equal to $47 \cdot 10^{-6}$ s.

To estimate the real value of the sensitive RC element resistance and capacitance has been carried out with multimeter GDM-8341 of GW INSTEK:

$$R_{real} = 99.84\ \text{Ohm}, C_{real} = 471.9\ \text{nF}. \tag{4}$$

Further, the measurements were carried out according to the method described above for tree-like quasi-distributed sensors. The experimentally obtained transient discharge process of the considered sensitive RC element is shown in Fig. 4.

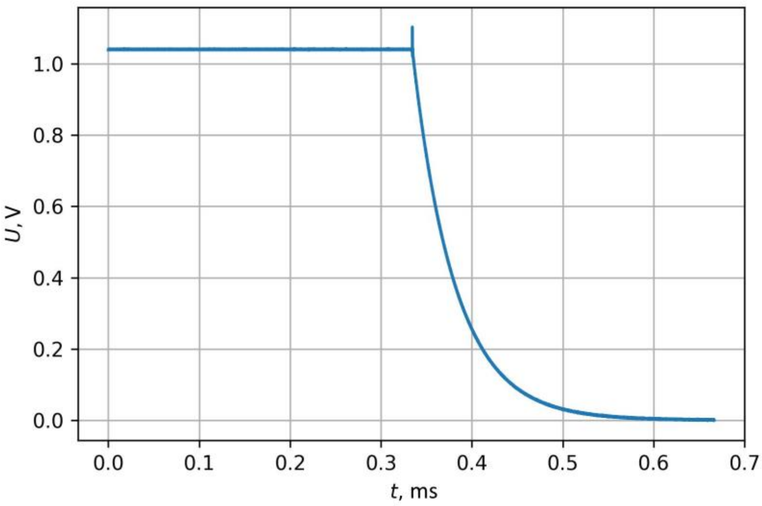
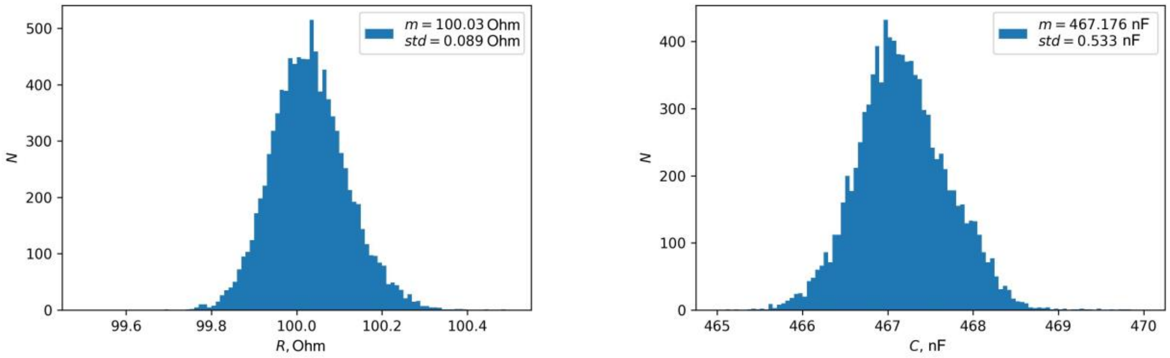


Fig. 4. The transient discharge process of a sensitive *RC* element

The resistance of the investigated *RC* element is determined by measuring the voltage drop across this element in the steady-state mode when the probing current flow through it. This moment corresponds to the initial section of the curve presented in Fig. 4. To reduce measurement error, the voltage and the probing current are averaged over 100 measurements. The histogram of resistance for the considering *RC* element estimated based on 10,000 measurements is shown in Fig. 5(a).



a b

Fig. 5. Histogram of the measured values of resistance (a) and capacitance (b) of the investigated *RC* element over 10000 measurements (where m is mean value; std is the standard deviation)

Analysis of the histogram (Fig. 5(a)) shows that the mean value of the resistance is 100.03 Ohm, and the standard deviation is 0.089 Ohm. Comparing the obtained values with real resistance values (4) it can be concluded that the absolute measurement error was 0.19 Ohm, and the relative measurement error was 0.19%.

To determine the value of the capacitance of the investigated *RC* element, the analysis of the discharge process, which corresponds to the second section of the graph shown in Fig. 4, is used. For this, the relaxation process is fitted by the function:

$$U(t) = U_m \cdot \left(1 - \exp\left(-\frac{1}{\tau} \cdot t\right)\right) + U_0, \tag{5}$$

where U_m, U_0 and τ are the parameters determined in the course of the fitting. After the time constant τ identification, it becomes possible to calculate the capacitance of the *RC* element according to (3). The histogram of capacitance values over 10,000 measurements is shown in Fig. 5(b). Analysis of the histogram shows that the mean value is 467.176 nF, and the standard deviation is 0.533 nF. Comparing the obtained values with the real values of capacitance (4), it can be noted that the absolute measurement error is 4.724 nF, which corresponds to the relative error of 1%.

Conclusion

The proposed quasi-distributed *RC* sensor with a tree-like structure allows measurements of several physical quantities due to the use of resistive and capacitive elements sensitive to different physical quantities connected in parallel to each other and forming a separate sensitive *RC* element. This provides a measurement of distributed physical fields in which this quasi-distributed *RC* sensor is located. At the same time, the tree-like structure of the connection of individual sensitive elements makes it possible to separate paths of the probing and measuring currents and significantly reduces the influence of other, not scanned, elements on the measurement results.

Evaluation of proposed sensor performance shows that the relative error for resistance measurement is about 0.19%, while the relative error of capacitance determination is less than 1%.

Acknowledgements

This work has been supported by the Agreement No. 075-03-2020-051/6 (No. project fzsu2020-0020) funded by the Ministry of Science and Higher Education of the Russian Federation.

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