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A NEW TRANSDUCER OF DOUBLE PROCESSING FOR CAPACITIVE TOMOGRAPHY

The paper presents a new solution of a system for the measurement of small capacities, applied in capacitive tomography. Some known versions of transducers have been discussed. Next, the author has presented his own solution, using a transducer of double processing. In the first step, capacity is changed into frequency, and next the frequency is changed into voltage. The change of capacity to frequency provides introduction of the measuring capacity into the resonant system of a generator. Small capacity changes in the capacitive tomograph influence the changes of the frequency generated by the generator. The proposed solution provides a far better stability of the measurement results related to typical solutions applied in capacitive tomography. The paper presents results of the tests performed for some systems and the obtained results were compared.

1. INTRODUCTION

Capacitance tomography includes measurements of capacity changes resulting from changes of the dielectric between the linings. In this case, the dielectric is the tested object; in this paper it is a liquid with gas bubbles.

Permittivity of liquids and gases is not the same, so it can be used for the identification of bubbles if these are present. The occurrence of a gas bubble in the measurement section causes a change of permittivity ε and results in a change of capacity.

A sensor for the capacitive tomograph is shown in Fig. 1. The measurement sensor includes a series of electrodes *1* arranged around the measured object. Since there are parasitic capacities, angular and radial screens *2* and *3* were used. Electrodes are usually made of copper or brass [2].

The capacitive method is often applied because it is simple and universal. Good results are obtained if the method is applied to objects of several centimeters. When insignificant capacity changes are measured, the measurement sensor should be calibrated – the signal-to-noise ratio must be as high as possible. In such a case, both the structure of the sensor and its electronic solution are of great importance.

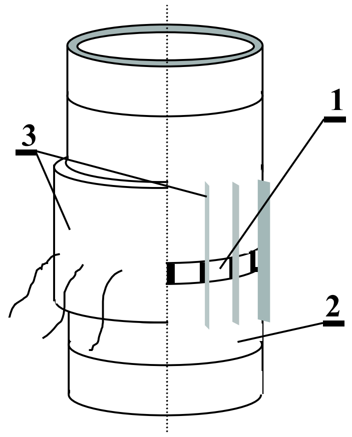

Fig. 1. Sensor structure.

2. A REVIEW OF MEASUREMENT CONVERTERS

This Chapter contains short descriptions of the already familiar solutions applied in process tomography. They can be easily compared with other solutions based on other approaches to the problem. Such a new version is presented in Chapter 3, and – as it appears – the new version can be successfully applied in practice.

- Resolution of images obtained with the known capacitive tomographs is relatively low in comparison with other applied tomograph techniques. It results from, among others, the limited sensitivity of the used converters. Quality of converters is testified by the following properties of the measuring system:
- The lowest capacity change measured at the given active surface of electrodes; in practice it is expressed in femtofarads (1[fF] = $1 \cdot 10^{-15}$ [F]).
- The ratio of signal to noise is as high as possible.
- A relatively wide range of the measured capacities. Depending on distances between the sensor electrodes, the capacity between the adjacent electrodes can be even 100 times greater than the capacity between the opposite electrodes.
- Processing rate.
- The system resistance to external disturbances, for example variation of supply voltage.

2.1. The measurement system based on an RC filter

The simplest measuring converter uses a high-pass RC filter (see Fig. 2) [1]. Here, the high-pass filter is connected to the input. In an element of the filter, capacity C_X, the signal from the generator and its frequency are measured. As capacity C_X changes, also the filter differentiation constant changes, and it causes a voltage change at the filter output. The diode detector system together with the operational amplifier OP2 is a demodulator of the pulse width. The output voltage V_{Out} is proportional to the measured capacity.

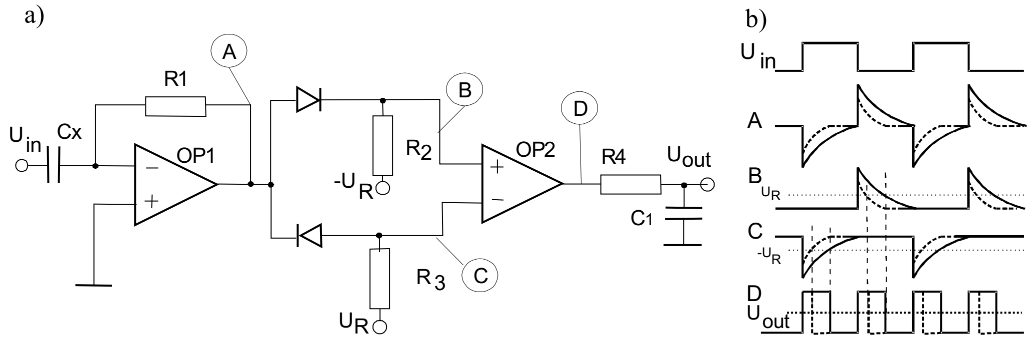

Fig. 2. System for capacity measurements using the high-pass RC filter: a) schematic diagram, b) signal waveform.

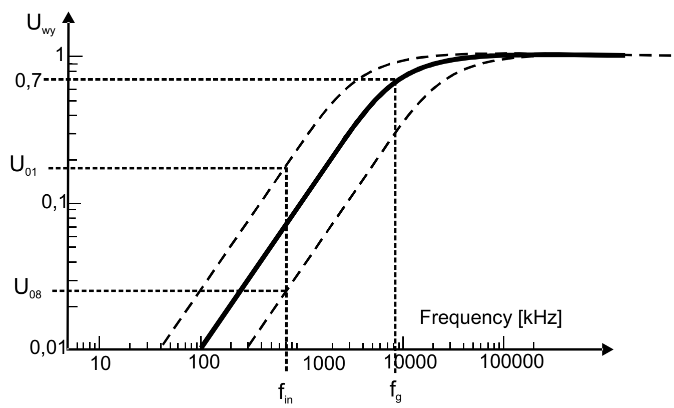

Fig. 3. Characteristic of conversion.

A voltage change at the converter output is dependent on the value of the condenser which retunes the limit frequency of the filter. This idea is shown in Fig. 3. The frequency of the signal delivered to the input of the measuring system is lower than the limit frequency of the converter. A capacity change causes a change of the filter limit frequency, which is connected with a change of the filter characteristic. The limit frequency of the filter is expressed as

$$f_g = \frac{1}{2\pi R_1 C_X}. \tag{1}$$

The filter of such a type has a characteristic slope 20 dB/dec, so voltage changes are dependent on the characteristic slope. Thus, small capacity changes cause small changes of the output voltage and an unfavourable ratio of the signal to noise.

2.2. A fast converter based on the RC filter

Capacity measurement using the RC filter is rather slow since output voltage measurement requires much time (unsteady states of the system must finish). Another solution is shown in Fig. 4. Here, one input signal period is enough for measurements. This solution is based on the generation of the waveform U_{in}, the shape of which is similar to a trapezoid [3] (Fig. 4).

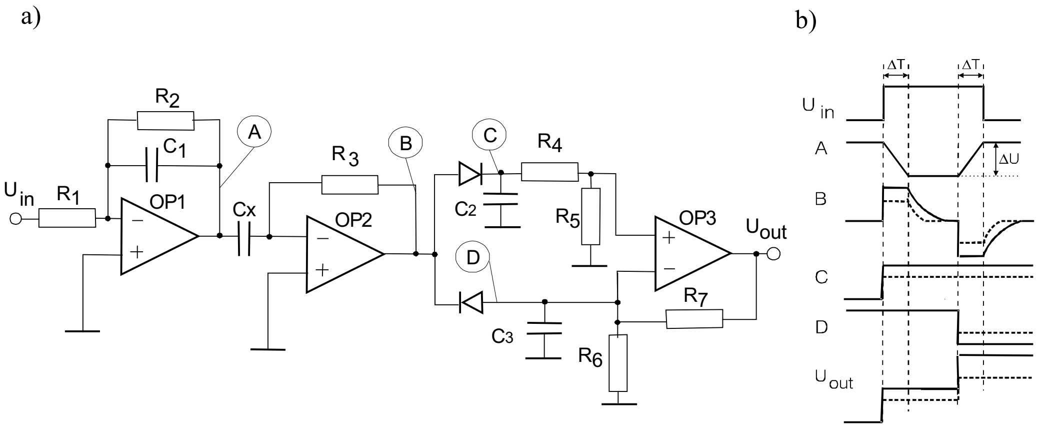

Fig. 4. A system with a generator of a trapezoidal waveform:
a) schematic diagram, b) signal waveform.

A signal from the generator is modified to the form of a rectangular signal U_{in}. The characteristic slope $\Delta U_{in}/\Delta T$ is a function of elements C_1, R_2. If values of resistors R2 and R1 are properly chosen, the maximum signal is determined. Depending on the measured capacity C_X, the value to which the condensers C_2 and C_3 are charged, changes. Voltage at the condensers influences the output voltage according to

$$U_{Out} = 2C_X R_3 \frac{\Delta U_{in}}{\Delta T}. \tag{2}$$

In this solution the tomograph works very quickly. One measurement lasts about 9 μs [4], therefore even some thousand frames per second can be registered.

2.3. A system with capacitance coupling

In the presented solutions the sensitivity of the output signal depends on the measured capacity and frequency of the inducing signal delivered to the system input. Figure 5 shows a system with capacitive coupling [5]. In this system, the circuit sensitivity is independent on the excitation frequency and depends only on the exciting voltage and capacitive coupling. It is very important in multifrequency systems.

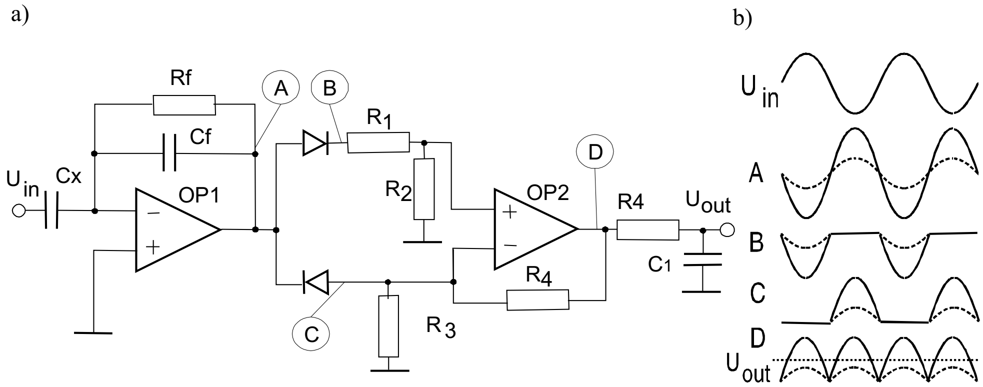

Fig. 5. A system with capacitive coupling: a) schematic diagram, b) signal waveform.

If the input voltage U_{in} is sinusoidal, the output signal U_{Out} is expressed by:

$$U_{Out} = \frac{j\omega C_X R_f}{1 + j\omega C_f R_f} U_{in}. \tag{3}$$

Capacity C_X is usually less than 1 pF and C_f and R_f are capacitive and resistance couplings of the operational amplifier. If the values of elements of the capacitive and resistance couplings are well chosen, i.e. if the capacitive coupling is dominating

$$\frac{1}{\omega C_f} << R_f, \tag{4}$$

then the equation for the output voltage will not be dependent on the excitation frequency

$$U_{Out} = \frac{C_X}{C_f} U_{in}. \tag{5}$$

2.4. A system with capacitance switching

Action of the systems with RC filters is very stable, but the filter time-constant should not be too small – in such a case the system cannot eliminate the noise of the measuring system. A larger time-constant causes more stable action of the filter, but the time until the output voltage stabilizes increases, so the measurement time increases, too. A lower time-constant causes faster action of the measuring system, but also an increase of the noise. Application of the filter reduces the possibility of an increase of measurement and data registration rates.

The system with capacity keying should reduce parasitic capacities, and – in consequence – increases the measurement rate. Figure 6 shows the system with capacity keying [6].

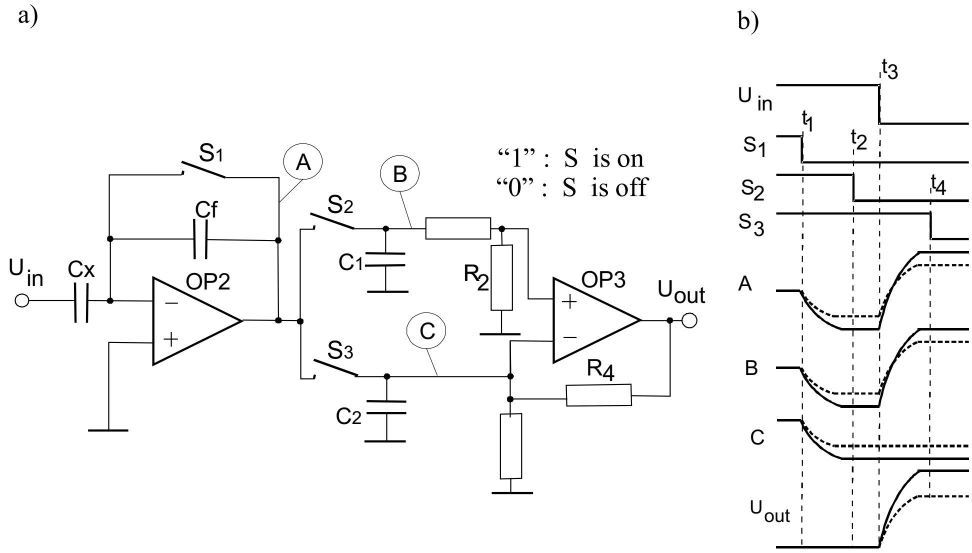

Fig. 6. System with capacity keying: a) schematic diagram, b) signal waveform.

The voltage of the capacitor loading C_f is measured. The voltage at the system output depends only on the measured capacity and the input signal amplitude, like in the system with coupling capacity, and it does not depend on the input signal frequency. Since only high or low states are delivered to the input, charge Q_C delivered to the measuring condenser depends on the difference between the high and low states.

$$Q_C = \Delta U_{in} C_X. \tag{6}$$

The output voltage depends on the capacitor charge according to

$$U_{Out} = -\frac{Q_C}{C_f} = -\frac{\Delta U_{in} C_X}{C_f}. \tag{7}$$

The measurement includes the following stages:

Step 1 – All the keys are connected, voltages U_1, U_2, U_3, U_{Out} are equal to about 0V. The condenser C_X is charged by Q_C.

Step 2 – At the moment t_1 the key S_1 becomes disconnected, the condenser C_f begins to be charged, and voltage U_1 at the amplifier output decreases proportionally to the voltage of the condenser C_f. Since the keys S_2 and S_3 are engaged, voltages U_2 and U_3 reach values equal to voltage U_1. Voltage U_{Out} at the output of the differential amplifier is equal to about 0V.

Step 3 – At the moment t_2 the key S_3 becomes disconnected. Then the charging state of the condenser C_f is stored. Because of the high input resistance of the operational amplifiers, voltage U_3 does not change to the condenser discharge at the amplifier input.

Step 4 – At the moment t_3 the input signal passes from the high state to the low one. It starts the discharge of the condensers C_X and C_f. Voltages U_1, U_2 and U_{Out} rise. Voltage U_3 does not change its value.

Step 5 – At the moment t_4 the key S_2 becomes disconnected and voltage U_2 is stored as well as U_{Out}. Voltage U_{Out} is stored in the computer memory and the measuring process can be started for another pair of electrodes.

2.5. A system with charge/discharge capacitance

Condenser charging and discharging could be achieved very quickly. Since condenser charging is realized only for one pair of electrodes, the system is resistant to disturbances and parasitic capacities. Moreover, good stability of measurements is obtained. A scheme of the system is shown in Fig. 7 [12]. The measuring system includes a set of analog keys $S_1 - S_4$; their sequent changing over causes charging or discharging of the measuring condenser C_X. The condensers C_i are responsible for a stable level of apparent mass and stability of measurements. Value of the condensers is about 0.1 μF.

Measurements of capacity using the charging-discharging method are performed with several stages [7].

Step 1 – All the keys are disconnected, voltages U_1, U_2, U_{Out} are about 0V. Condenser C_X is discharged.

Step 2 – The key S_3 is connected and joined with the measuring system with the operation amplifier A_1 and just after that, at moment t_1 the key S_1 is connected and the condenser charging starts. The waveform of voltage U_1 is dependent on the differentiation constant being a function of C_X and R_f.

Step 3 – Disconnection of the keys S_3 and S_1 – it brings the end of the condenser charging process.

Step 4 – Connection of the key S_4 with the measuring condenser with the operation amplifier A_2. At moment t_2 the key S_2 is connected and condenser discharging begins. Voltage U_2 changes in differentiation functions and the differentiation constant is equal to the product of C_X and R_f.

Step 5 – Disconnection of the key S_4 and next the key S_2 – the condenser discharging ends. After that stage the process begins once again with constant frequency of changing over the keys (usually some MHz).

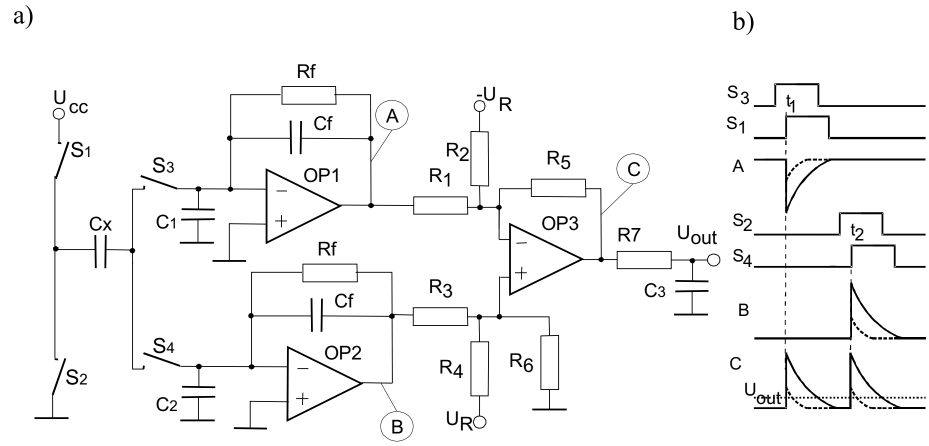

Fig. 7. The system with charge/discharge capacitance:
a) schematic diagram, b) signal waveform.

In a typical cycle, voltages U_1 and U_2, are dependent on frequency of changing over and the measuring capacity C_X. Since the process of charging and discharging is repeated with frequency f, the following currents of charging and discharging are averaged in two detectors and they form two voltage waveforms with the mean value [10]:

$$U_1 = -fU_C R_f C_X + U_{e1}, \tag{8}$$

$$U_2 = fU_C R_f C_X + U_{e2}, \tag{9}$$

where: f – frequency of a cycle of charging and discharging [Hz], U_C – voltage of the condenser charging [V], U_{e1}, U_{e2} – voltages of the offset for the operation amplifiers A_1 and A_2 [V].
The output voltage is dependent on the difference between voltages U_1 and U_2 and it is expressed by

$$U_{Out} = U_2 - U_1 = 2fU_C R_f C_X + U_{e2} - U_{e1}. \tag{10}$$

2.6. Measurement of capacity in the LC generator

The measuring systems using changes of capacity into frequency are very good solutions because frequency can be measured with high resolution, and it is very important during measurements of small changes of capacity. A scheme of the measuring system is shown in Fig. 8 [8]. Interelectrode capacity is an element of the LC filter, determining the frequency of the generator vibrations. The resultant permittivity of the dielectric ε_r is a *function of permittivity of particular phases, but in the resultant capacity also the channel permittivity and the connected capacity C_Z: should be taken into account.*

$$C = \frac{C_Z C_X}{C_Z + C_X}. \tag{11}$$

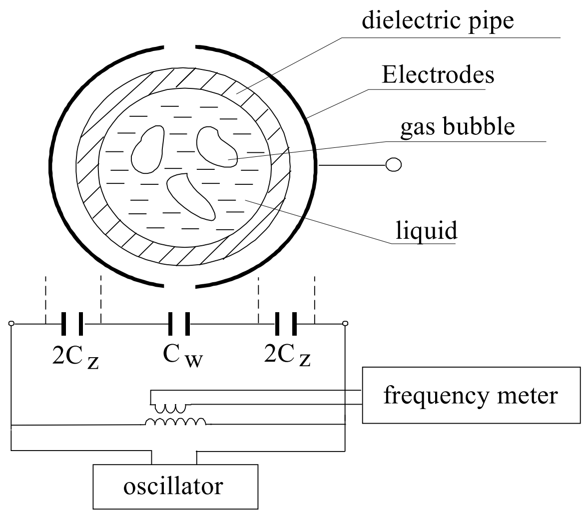

Fig. 8. A scheme of the measuring system in the LC generator.

In the oscillator system, the generated frequency is given by the general expression:

$$f = \sqrt{\frac{1}{2\pi L\,(C + \Delta C)}}, \tag{12}$$

where ΔC is the capacity change resulting from a change of the flow structure.

The influence of the conductance component of the interelectrode admittance can be eliminated by application of high frequency supplying the converter, much higher than the limit frequency being the inverse of the time-constant of the relaxation processes in a given medium.

2.7. Capacity measurement in the RC generator

Measurements of frequency of a rectangular waveform do not require zero-detection systems in frequency meters; moreover, they allow to join the converter directly to the processor, in a way that the measurement system becomes simple. Capacity can be changed into frequency in the RC generator system using the Schmitt trigger. A scheme of the measuring system is shown in Fig. 9 [9].

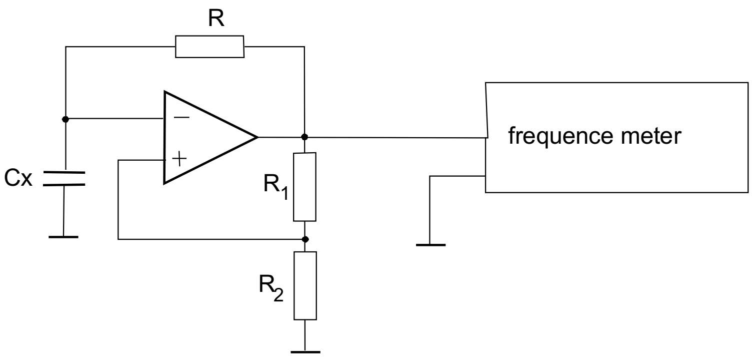

Fig. 9. A scheme of the measuring system in the RC generator with the Schmitt trigger.

In this system, the measuring capacitance C_X is charged by the resistor R. These elements form a negative feedback loop. A positive retroactive circuit including the elements R_1 and R_2 requires changing over the amplifier from one saturation state to the other. The input voltage change causes charging and discharging of the measuring condenser. The frequency generated by the system is expressed by

$$f = \frac{1}{3RC_X \ln\left(1 + \frac{2R_2}{R_1}\right)}. \tag{13}$$

3. THE SYSTEM WITH DOUBLE PROCESSING

In many fields, stability of measurements is more important than their rate. In such a case the transducer of double processing can be applied. For example, it can be used for the determination of the mean volume fraction of phases in a two-phase gas-liquid flow where a change range is wide. It is necessary to apply a transducer with high signal amplification in a wide range for a high signal-noise ratio.

The systems with generators give good stability of measurements, but the frequency measurement rate is much smaller than in the systems with voltage measurements. A system with double processing is another solution (Fig. 10). At first, capacity is converted into frequency in the generator system with the Wien bridge. Next, a signal from the generator is changed into voltage in the low-pass filter with the limit frequency lower than the least frequency generated by the generator.

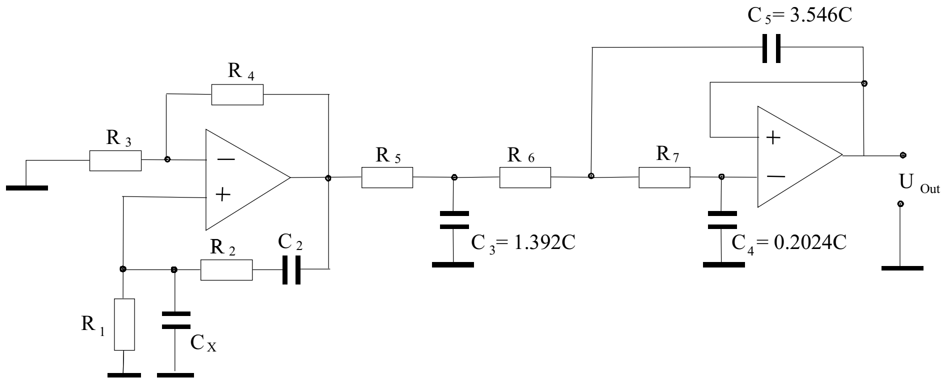

Fig. 10. A scheme of the system with double processing.

The frequency generated by the generator depends on the bridge elements R_1, R_2, C_2 and C_X. The measuring condenser is one of these elements and it causes a change of the generator output frequency:

$$f = \frac{1}{2\pi\sqrt{R_1 C_X R_2 C_2}}. \tag{14}$$

The following equation expresses the amplitude condition:

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} + \frac{C_X}{C_1}. \tag{15}$$

From Eqs. 14 and 15 it appears that a change of the measured capacity influences both the output frequency and the output voltage amplitude U_1. It is very important because in this way we obtain much higher changes of the output voltage after processing by the low-pass filter in relation to the systems where only the frequency changes.

Application of the low-pass filter causes that the waveform amplitude at the output changes when frequency delivered to the input. Thus, changes of the generated signal amplitude can be observed. Parameters of the filter should be properly chosen: the minimum frequency generated by the generator should satisfy the following relationship:

$$f_{\min} > f_{-3bB} = \frac{1}{2\pi RC}. \tag{16}$$

The applied filter is of third order, so it is possible to obtain changes of the output voltage related to frequency changes 60dB/dec.

Voltage was measured at the transducer output for a sensor including 16 electrodes. The sensor diameter was 150 mm, and the pipeline was filled with distilled water. The test stand is shown in Fig. 11. The pipeline 1 with the measuring sensor 2 was progressively filled with water, and signal values were measured at the output of the measuring transducer. In order to calibrate the sensor, gas and liquid flow were eliminated, so the measurements were performed in static conditions. Thus, the influence of variable conditions caused by the gas and liquid flow could be neglected. In such a situation, the measurement results are influenced by the degree of pipeline filling (observed at the indicator 3).

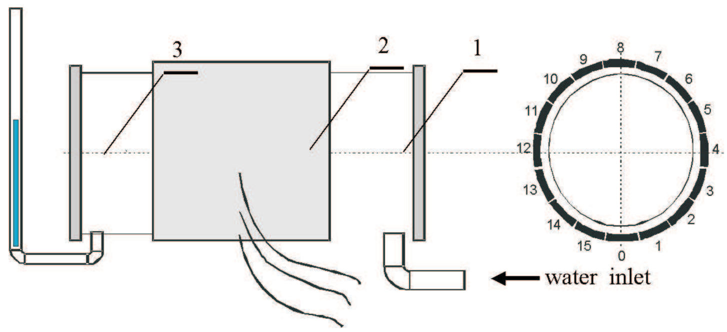

Fig. 11. The test stand.

The voltage was measured at the converter output connected to the sensor including 16 electrodes. In the case of the condenser using the generator with the Wien bridge (Fig. 12), a change of the measured capacity causes both a change of voltage frequency Ug and a change of the signal amplitude. Figure 11 shows the results of the signal amplitude measurements and frequency changes for the opposite electrodes. In the curves, 0% means that the sensor is completely filled with water, 100% means that it is filled with air.

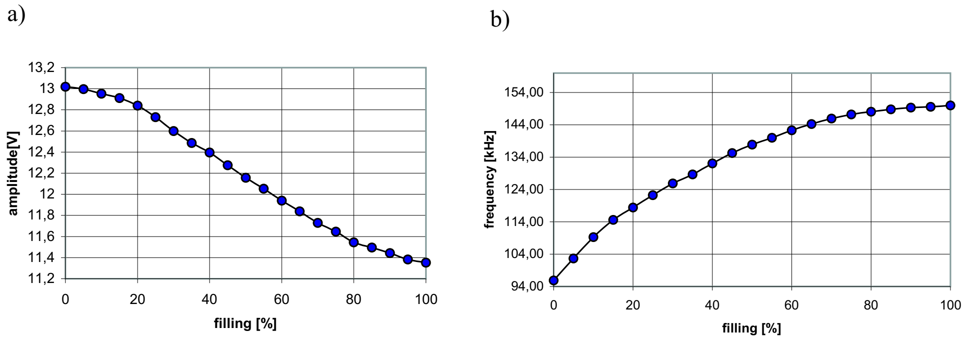

Fig. 12. Processing characteristics for the condenser with the Wien generator:
a) voltage changes depending on filling of the sensor,
b)frequency changes depending on filling of the sensor.

The tests were performed for two pairs of electrodes. Figure 13 shows the results of measurements of voltage changes at the converter output depending on the sensor filling with water. The results were related to two opposite electrodes (Fig. 13b) and two adjacent electrodes (Fig. 13a). It is very important in the image reconstruction, applied in capacitive tomography [11]. From the presented characteristics it appears that large amplification of the measuring signal is obtained. Nonlinear characteristics of processing could be disadvantageous.

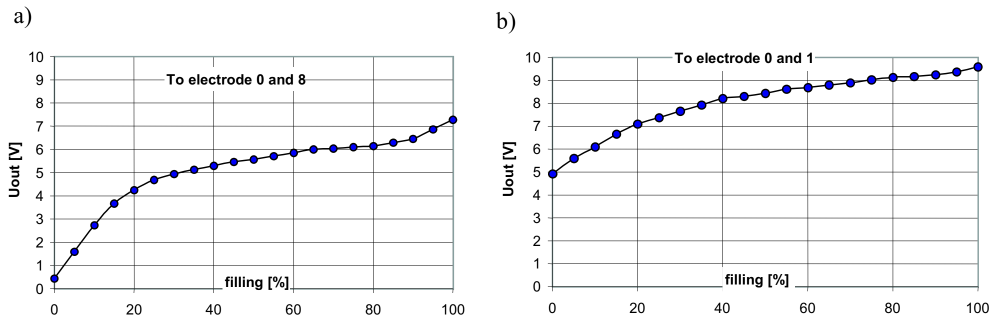

Fig. 13. Results of voltage measurements at the converter output for:
a) adjacent electrodes, b) opposite electrodes.

4. SUMMARY

From the tests of a new measuring converter it appears that the tested system is stable. It is very important for the tests of a flow performed over a long time. The proposed solution gives high amplification of the converter and good stability of measurements. It is caused by the applied simultaneous detection of the changing frequency and the signal amplitude from the generator. It causes a high signal amplification at the converter output with no need of application of large amplifications from the signal amplifiers.

Unfortunately, the processing rate is rather slow – in the model sensor containing 16 electrodes the measurement rate was up to 5 frames/sec. In some cases it can be insufficient. The proposed solution cannot be applied in systems with high dynamics. However, it can be used for measurements of two-phase laminar flows.

Figure 14 shows voltage changes after signal processing in the low-pass filter (see Fig. 7) into voltage. The results were compared with the results of voltage measurements for the same sensor using the system from Fig. 4.

Output voltage stability was measured for the tested transducers. The test results are shown in Fig. 15. The deviation means percentage between the minimum and maximum values measured over 5 minutes, related to the mean value. Both transducers show greater unstabilities of the output voltage for low capacitances, i.e. for the sensor filled with air. However, the transducer with double processing can be characterized by lower unstabilities.

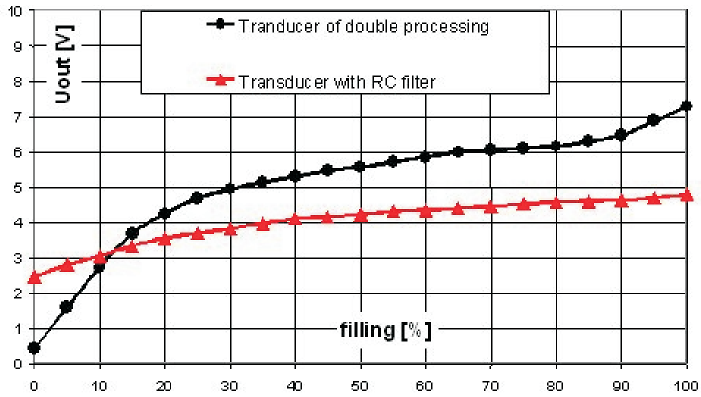

Fig. 14. Comparison of measurement results for transducers with RC filter and of double processing.

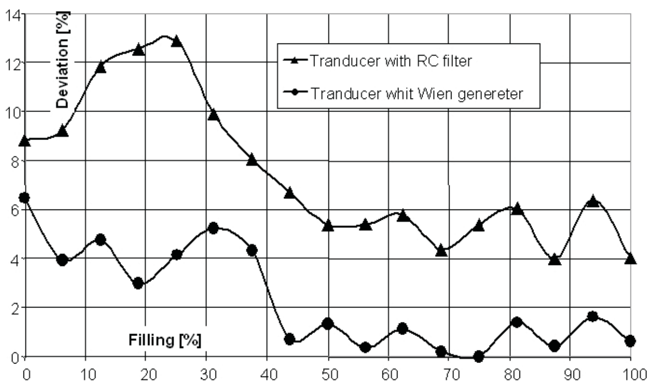

Fig. 15. Output voltage stability of measurements.

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