DEVELOPMENT OF A HIGH-SPEED MULTICHANNEL IMPEDANCE MEASURING SYSTEM

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Abstract: Impedance sensors are found in many industrial applications. Multipoint and fast impedance measurement is required for some applications, for instance in the investigation of multiphase flows or the measurement of distributed sensors. In this paper, we describe a new high-speed multichannel impedance measuring system, which may be used for the evaluation of capacitance and resistive loss of multiple sensors. System is based on measurement at two selectable single frequencies. The system was evaluated against reference measurement showing good agreement.

Key words: impedance measurement, high-speed, multichannel system.

1. INTRODUCTION

Impedance sensors, in which the measurand causes a variation of an electrical characteristics such as resistance or capacitance, have found widespread use in industrial applications mainly due to their simplicity, low fabrication costs and robustness [1]. Impedance measurement is a common tool for the characterization of electrical properties of materials and substances, in which measurement times of seconds to minutes are used to achieve high measurement accuracy in the analysis [2]. However, in industrial applications, measuring times in the range of microseconds to milliseconds are required in order to investigate dynamic processes, e.g. mixing of substances in chemical reactors, multiphase flow in pipelines. Accuracy requirements in such applications are less critical, since substances involved, and consequently their electrical properties, are known a-priori. In addition, multipoint impedance measurement is often also required in order to obtain spatial or distributed information, for instance, in the imaging of multiphase flows [3,4] or for the measurement of distributed sensors [5,6]. Hitherto used systems for multichannel measurement are limited to a single electric parameter such as resistance or capacitance [3-6].

Many sensors are modeled as parallel circuit of resistor and capacitor. In this contribution, we introduce a novel approach to fast measurement of impedance in its two components (resistance and capacitance) utilizing two frequencies. Based on a multiplexed excitation-probing scheme, a multichannel system is proposed which allows for multipoint measurements.

2. MEASURING CIRCUIT

2.1. Basic circuit analysis

For impedance measurements we chose the circuit synonymously know as transimpedance amplifier, auto-balancing bridge or current-voltage converter, as depicted in figure 1. Since the developed system is meant to be used for identifying different fluids in a similar approach as for [4,5], the electric model that better represents the characteristics of a fluid is a parallel RC circuit [7]. Thus, the unknown impedance was assumed to be capacitive only. In figure 1, $\mathbf{V}_\mathrm{i}$ is the excitation voltage, $\mathbf{Z}_\mathrm{x}$ represents the unknown impedance and C_f along with R_f the feedback network. Furthermore, C_s1 and C_s2 represent the stray capacitances to ground which are caused, for instance, by cables used to connect the circuit with a sensor. In principle, these stray capacitances have no influence in the circuit since C_s1 is directly driven by the source voltage and C_s2 is virtually grounded by the opamp.

The impedance is determined by measuring the voltage at the opamp output. Assuming that the opamp is ideal the output voltage $\mathbf{V}_\mathrm{o}$ is determined by

$$\frac{\mathbf{V}_\mathrm{o}}{\mathbf{V}_\mathrm{i}} = -\left(\frac{G_\mathrm{x} + j\omega C_\mathrm{x}}{G_\mathrm{f} + j\omega C_\mathrm{f}}\right) \tag{1}$$

where $\omega = 2\pi f$ and f is the frequency of the sinusoidal excitation signal.

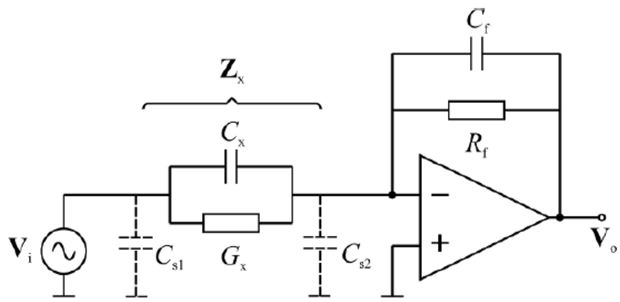

Fig. 1. Practical circuit for measuring impedances formed as parallel circuit of a capacitor and a resistor.

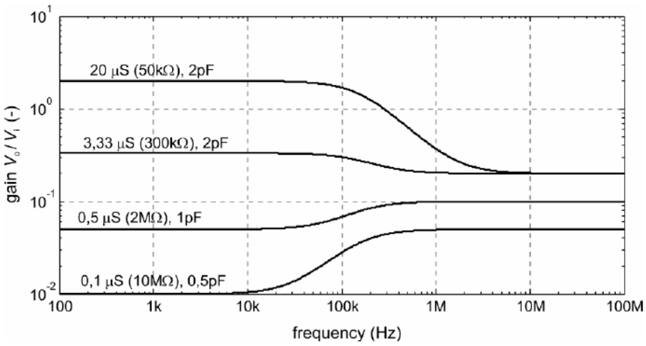

Fig. 2. Frequency response for components values $C_f = 10pF$, $G_f = 10\mu S$ (100 kΩ), C_x and G_x (R_x) are indicated in the plots.

The Bode Diagram for the amplitude of eq. (1) using typical R and C values is shown in figure 2.

Two plateaus can be readily identified, one in low and other in high frequency. Knowing that a capacitor works as an open circuit in DC, the smaller is the frequency, the lower the influence of the capacitive part, leaving only the resistive part. On the other hand, the higher is the frequency, the higher the influence of capacitive part and the lower is the resistive part.

The magnitude of each plateau is given by the quotient of G_x/G_f and C_x/C_f which are obtained taking the limit for $f \to 0$ and $f \to \infty$ of the modulus of equation (1), in the form

$$\left|\frac{V_o}{V_i}\right| = \frac{\sqrt{G_x^2 + (2\pi f)^2 C_x^2}}{\sqrt{G_f^2 + (2\pi f)^2 C_f^2}} \quad (2)$$

A simplified way to view the behavior of auto-balancing bridge is according to the graph showing in the figure 3 below. Further shown in the figure, is the operational amplifier frequency response.

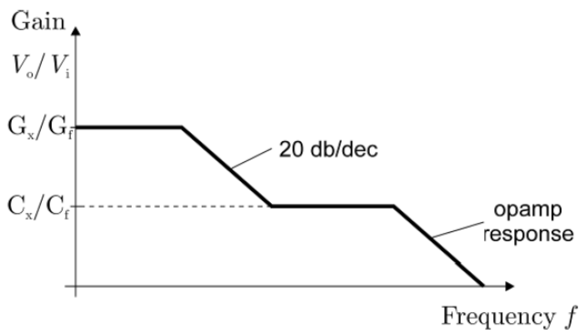

Fig. 3. Asymptotic simplified frequency response of a practical auto-balancing bridge circuit taking into account the opamp non-ideal frequency response.

In principle, any two frequencies may be chosen for determining the unknown components. The simplest choice, however, is to select two frequencies located exactly in each plateau. Hence, the two unknown parameters are found by:

$$G_x = G_f \left|\frac{V_o}{V_i}\right|_{f=f_{\text{low}}} \quad (3)$$

$$C_x = C_f \left|\frac{V_o}{V_i}\right|_{f=f_{\text{high}}} \quad (4)$$

Since the resistance R is directly proportional to the conductivity of the material, and the capacitance C is directly proportional to the electric permittivity of the material, the measurement of the parameters resistance and capacitance are an indication of the electrical conductivity and permittivity of the substance being measured. In last analysis, substances can be distinguished from each other and thus correctly indentified based on these measurements.

For instance, in the field of multiphase flow measurement, featuring two distinct parameters of the substance, we can identify up to three substances flowing simultaneously in a pipeline, or identify a mixing of substances in chemical reactors, for example, with more accuracy than a technique that identifies only one parameter.

2.2. Multichannel system

The developed multichannel system is schematically shown in figure 4. In the present paper, however, only a single excitation and single receiver circuits are evaluated.

The hardware developed is divided in four parts. The first part is the transmitter board, in which there are two direct digital synthesizers (DDS) (AD9833 from Analog Devices) for generating the two sinusoidal signals at different frequencies. The DDS is a programmable integrated circuit, where we can select sinusoidal, triangular or square wave outputs and in the case of the AD9833, we can generate signals up to 12.5 MHz. The DDS are programmed by a data acquisition card (PCIe-7841R National Instruments) using SPI (Serial Peripherical Interface) and making the user interface for software developed in LabView.

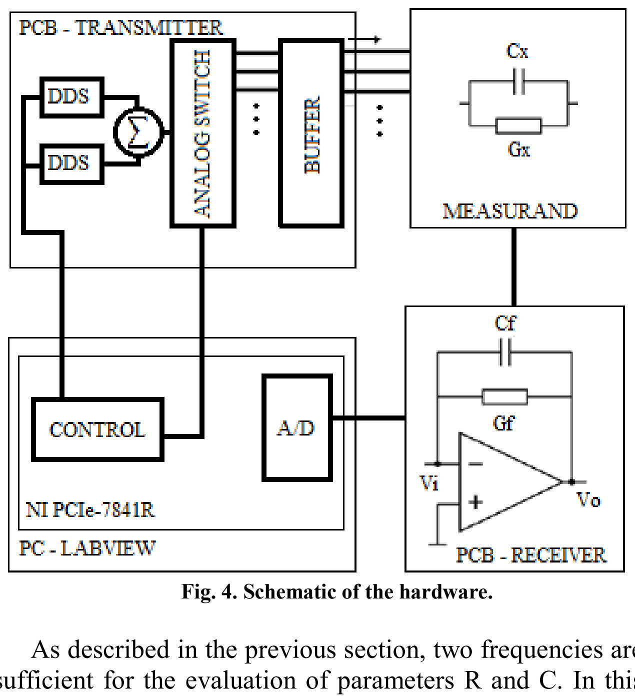

Fig. 4. Schematic of the hardware.

As described in the previous section, two frequencies are sufficient for the evaluation of parameters R and C. In this way, a signal composed by the single frequencies is generated by summing together the signals of two separated DDS circuits by means of an adder circuit using operational amplifier. The excitation signal (containing two frequencies) is connected to up to eight excitation electrodes with help of analog switches. The non-selected channels are grounded in order to allow for a multiplexed excitation scheme. Buffers at the output assure that the excitation signals have low impedance.

The signal than pass trough the measurand (as previously described we assume to be formed by the parallel circuit of a R and C) and enters the receiver board, where current signals are converted into voltage signals by a transimpedance amplifier (auto-balancing bridge circuit). Voltage signals from opamp are A/D-converted at the PCIe-7841R. The digitalized signals are processed in the host PC with a program based on LabView. The amplitudes of the excitation signals are determined in the program based on Fast-Fourier transform (FFT) processing tools. In order to allow for fast response, the each channel is sampled at 200 kHz (maximum possible by the card) and 32 samples are processed, thus 6.25 kHz repetition frequency is possible at up to eight channels (maximum number of channel by the card).

3. RESULTS

Initial tests of developed system involved tests to evaluate the step response and frequency response. Further, accuracy of developed system was evaluated by measuring different impedances with known values consisting of a parallel RC circuit, as described below.

3.1. Frequency response

A sinusoidal voltage signal swept in frequency from 2 kHz to 20 MHz was used to test the frequency response of auto-balancing bridge circuit. The signal was applied to input of a known RC circuit (measurand) which was connected to the auto-balancing bridge circuit. The output signal of the receiver module was measured with an oscilloscope. Thus, we surveyed the frequency response curves for four different combinations of resistors and capacitors with values similar to the figure 2 for comparison. The obtained frequency responses are depicted in figure 5.

The two plateaus can be clearly seen in the experimental results as well as the shape of the curves fit very well with theoretical response, as anticipated in section 2.1. Only the absolute measured values (fig. 5) slightly deviate from the theoretical ones (fig. 2). This fact, implies that that the circuit input-output response must be adjusted by using some reference components.

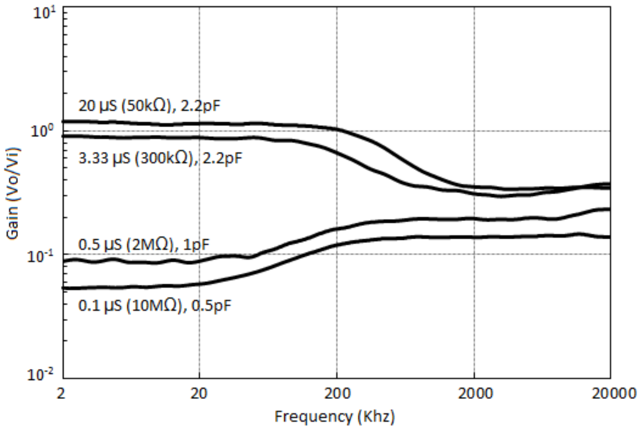

Fig. 5. Frequency response in circuit for components values Cf = 10pF, Gf = 10µS (100 kΩ), Cx and Gx (Rx) are indicated in the plots.

3.2. Step response

In order to verify the maximum achievable repetition in a multichannel system, the step response of auto-balancing bridge circuit was evaluated. The system is intended to be used a repetition rate of 4 kHz. Using a waveform generator (Agilent 33220A) in amplitude modulation function, in which a carrier sine wave of 1 MHz was modulated with a square wave signal of 50 kHz, the step response of circuit can be evaluated. An oscilloscope at the output shows the resulting waveform, as shown in figure 6. In this experiment RC parallel circuit used was 2.2pF and 1MΩ.

As shown in the figure the time response of carrier of 1 MHz is almost instantaneous for the time scale used, so that system can be well applied in the intended 4 kHz repetition frequency with no loss in the accuracy of measurements.

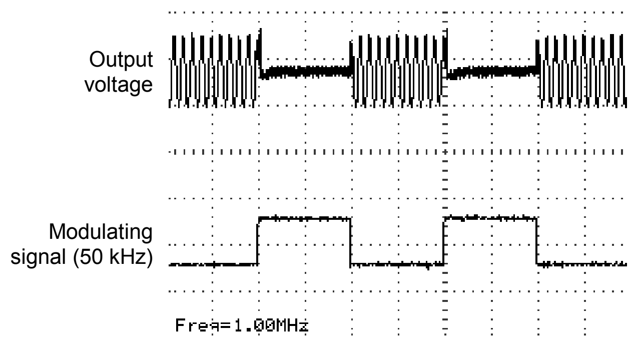

Fig. 6. Step response in circuit for a rate of 50kHz.

3.3. Impedance measurement

In order to evaluate the accuracy of circuit, different combinations of known resistor and capacitors were measured. The two frequencies chosen for evaluating the amplitudes were 10 kHz (resistance plateau) and 950 kHz (capacitance plateau). Since sampling frequency of data acquisition card was 200 kHz, the 950 kHz component is undersampled, appearing as 50 kHz at the determined frequency spectrum via FFT. Nevertheless, its amplitude is correctly determined. Excitation amplitude of two components was kept constant, and amplitude of output signals was determined. Twenty two combinations of resistors and capacitors were measured, with values between 100kΩ - 2.2MΩ and 0.5pF - 10pF. The parity plots of measured (eq. 3 and 4) and reference values are shown in figures 7 and 8. Deviations from references values are below 10% which considering the fast repetition frequency is satisfactory. Higher accuracy may be achieved by lowering the repetition frequency of measurements, thus decreasing random errors.

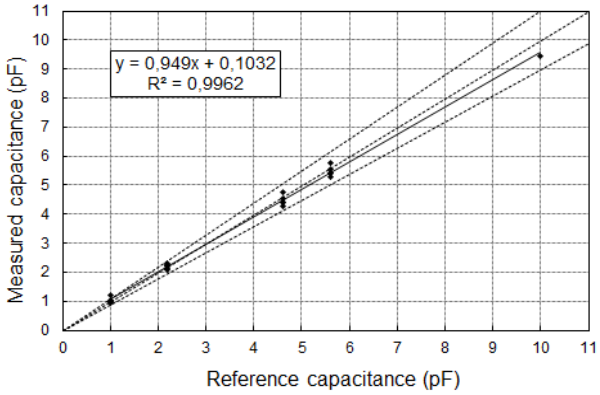

Fig. 7. Parity plot of measured and reference values of capacitance. The dotted lines show the +/-10% deviation from ideal line.

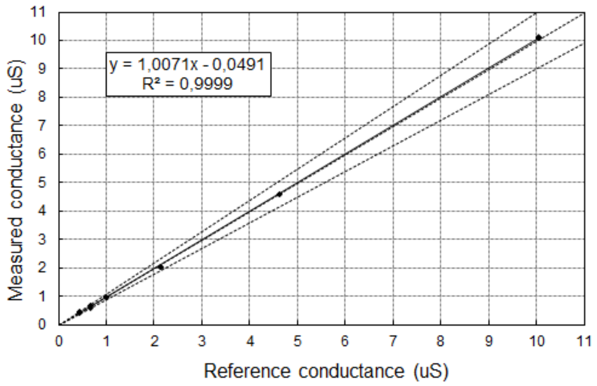

Fig. 8. Parity plot of measured and reference values of conductance. The dotted lines show the +/-10% deviation from ideal line.

4. CONCLUSIONS

A new multichannel system for multipoint impedance measurement of capacitive and resistive component was presented and tested. The impedance is determined based on the measurement of amplitudes at two distinct frequencies. Preliminary results with single-point reference impedances show good accuracy at high-speed measurements. Further work will be related in deploying the multichannel system for high-speed multiphase flow measurement, for instance in wire-mesh sensors [3,4]. Hereby flow of mixtures with up to three different components may be investigated, as is very desired in the oil industry to investigate the flow of oil, water and gas.

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