Development of the injection current source for the information-measuring system of electrical impedance tomography of biological object

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Abstract. To implement an electrical impedance tomography device, it is necessary to develop one of its most important components - an injected current source, which characteristics affect the metrological characteristics of whole device. In this regard, the task was set to develop such a current source that satisfies a number of requirements regarding the stability of its operation in a given range of frequencies and output current amplitudes, as well as load resistances. As a result of the work performed, a voltage-controlled injected current source for an electrical impedance tomography device was developed, manufactured, and investigated. The error of the amplitude of the output current and the error of the frequency of the output current were studied using a mathematical model and during a full-scale experiment. Active resistance and a biological object were used as a load. As a result of the simulation, it was found that the error in the amplitude of the output current does not exceed 1-5% for a given range of load resistances and frequencies.

1 Introduction

One of the main components of an electrical impedance tomography (EIT) device, the characteristics of which affect the stability and metrological characteristics of the entire device, is the injected current source.

The developed CS injected current source for the EIT device must meet the following requirements:
- control of the shape, frequency $f_I$ and amplitude $I_m$ of the current by control voltage $U_{cont}$;
- amplitude $I_m$ output current $I$ through load $R_{load}$: 1-5 mA [1];
- error $\delta_I$ amplitude $I_m$ output current $I$ – no more than 5%;
- maximum frequency $f_{\text{max}}$ – 100 kHz;
- grounded load with resistance $R_{load}$ 50 Ohm -2 kOhm [1].

These requirements are met by an CS circuit with automatic measurement and regulation of current in the load [2, 3].

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2 Materials and methods

The functional diagram of the developed source for the EIT device is presented in Figure (1).

![Fig.1. Functional diagram of CS EIT device](image)

The output current $I$ is directly proportional to the voltage drop $U_s$ across the resistor $R_s$ and inversely proportional to the resistance of the resistor $R_s$. To measure the voltage drop $U_s$, a differential amplifier is used on the operational amplifier $DA_2$. If the gain of the differential amplifier $[4] \ K_U = 1 \ (K_U = \frac{R_a}{R_b}, \ R_a = R_1 = R_3; \ R_b = R_2 = R_4)$, then the output voltage of the operational amplifier $DA_1$ is set such that the voltage drop $U_s$ across the resistor $R_s$ is equal to the input voltage. Increasing the gain $K_U$ allows to proportionally reduce the nominal resistance of the resistor $R_s$. The maximum value of the load resistance is determined by the ratio of the maximum output voltage of operational amplifiers $DA_1, DA_2$ to the amplitude $I_m$ output current $I$ through the load $R_{load}$.

The circuit diagram of the developed CS injected current source for the EIT device is shown in Figure 2.

![Fig.2. Schematic diagram of CS EIT device](image)

When power is connected, all EIT device units are supplied with supply voltage. The shape and frequency $f_I$ of the current $I$ at the $OUT$ pin of the current source correspond to the shape and frequency $f_{cont}$ of the control signal $U_{cont}$ at the $IN$ pin of the current source. The amplitude $I_m$ of the current $I$ at the CS output is proportional to the amplitude $U_m$ control voltage $U_{cont}$ at the $IN$ CS pin. The current source starts working immediately after power appears. Current source $IN$ pin is connected to the common point through resistor $R_1$ to avoid
the appearance of current $I$ at the OUT pin of CS due to the effect of induced voltage on the IN pin of CS.

3 Simulation of a current source circuit

Schematic electrical diagram of the developed CS for the EIT device in the Micro-Cap 10.0 circuit modeling package [5] is shown in Figure (3). The GENERIC model was selected as an op-amp with parameters corresponding to the parameters of the Texas Instruments TL 07 CP op amp [6].

![Schematic diagram of CS EIT device in the Micro-Cap environment](image)

Based on the simulation results, an estimate was made of the error $\delta_I$ of the amplitude $I_m$ of the current $I$ through the load $R_{load}$ under various CS operating modes. The model parameters simulating various CS operating modes are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load resistance $R_{load}$, Ohm</td>
<td>50;1 00;500;1000;1500;2000</td>
</tr>
<tr>
<td>Amplitude $U_m$ control voltage $U_{cont}$, V</td>
<td>0.22;0.44;0.66;0.88;1.1</td>
</tr>
<tr>
<td>Resistance resistor $R_s$, Ohm</td>
<td>220</td>
</tr>
<tr>
<td>Frequency $f_{cont}$ control signal $U_{cont}$, kHz</td>
<td>1;10;20;30;40;50;60;70;80;90;100</td>
</tr>
</tbody>
</table>

$I_m$ of the current $I$ through the load $R_{load}$ was calculated. Next, the calculation of the reduced $\delta_I$ error in establishing the amplitude $I_m$ of the current $I$ was carried out. The calculation is made according to the formula:

$$\delta_I = \left| \frac{I_{m_{mod}} - I_m}{I_M} \right| \cdot 100\%,$$

where $I_{m_{mod}}$ is the calculated value of the amplitude $I_m$ output current $I$; $I_m$ — specified value of the amplitude $I_m$ output current $I$; $I_M$ — maximum specified value of amplitude $I_m$ output current $I$.

Estimation of the spread of error values $\delta_I$ of amplitude $I_m$ output current $I$ depending on the load resistance $R_{load}$ is presented in the form of a Box-Whiskers diagram in Figure (4). The diagram was built using the Statistica package.
Fig. 4. Estimation of error values $\delta_I$ for different values of $R_{\text{load}}$ and $f_{\text{cont}}$

Estimation of the spread of error values $\delta_I$ of amplitude $I_m$ output current $I$ depending on the frequency $f_{\text{cont}}$ of the control signal $U_{\text{cont}}$ is presented in the form of a Box-Whiskers diagram in Figure (4) too.

As can be seen from Figure 4, as the value of the load resistance $R_{\text{load}}$ increases, the error $\delta_I$ of the amplitude $I_m$ increases output current $I$. This is caused by the influence of the load on the current-generating circuit. The minimum error $\delta_I$ is observed at $R_{\text{load}} \approx R_s$. With increasing frequency $f_{\text{cont}}$ of the control signal $U_{\text{cont}}$, the error $\delta_I$ of the amplitude $I_m$ output current $I$ also increases, but the influence of frequency $f_{\text{cont}}$ is significantly less than the influence of the resistance value $R_{\text{load}}$. The increase in error $\delta_I$ with increasing frequency $f_{\text{cont}}$ is caused by the imperfection of operational amplifiers. According to the simulation results, the error $\delta_I$ of the amplitude $I_m$ output current $I$ does not exceed 1% at resistance values $R_{\text{load}} = 50...100$ Ohms and frequency $f_{\text{cont}} = 1...100$ kHz. With load resistance $R_{\text{load}} = 0.5...1$ kOhm and frequency $f_{\text{cont}} = 1...100$ kHz error $\delta_I$ amplitude $I_m$ output current $I$ does not exceed 5%.

4 Making a current source

The electrical circuit diagram of the developed CS injected current source for the EIT device is shown in Figure (2).

When power is connected, all EIT device units are supplied with supply voltage. The shape and frequency $f_I$ of the current $I$ at the OUT pin of the current source correspond to the shape and frequency $f_{\text{cont}}$ of the control signal $U_{\text{cont}}$ at the IN pin of the current source. The amplitude $I_m$ of the current $I$ at the CS output is proportional to the amplitude $U_m$ control voltage $U_{\text{cont}}$ at the IN CS pin. The current source starts working immediately after power appears. IN CS pin is connected to the common point through resistor $R_1$ to avoid the appearance of current $I$ at the OUT pin of CS due to the effect of induced voltage on the IN pin of CS. For selected operational amplifiers DA1, DA2, the maximum output voltage is at least ±10 V.

A drawing of a printed circuit board has been developed and an assembly drawing of the CS injected current source for the EIT device is shown in Figure (5). Development carried out in DipTrace software [7].
5 Results and discussion

In experimental studies of CS for EIT device, it is necessary to check the following characteristics:
- error $\delta_f$ of output current $I$ frequency $f_I$;
- error $\delta_I$ output current $I$ amplitude $I_m$.

To experimentally estimate the error $\delta_f$ of the frequency $f_I$ of the output current $I$, we will estimate the frequency $f_{\text{load}}$ voltage $U_{\text{load}}$ at the reference load $R_{\text{load}}$. Load resistance $R_{\text{load}} = 220$ Ohm. To measure frequency, a frequency meter FM-63 is used. The main characteristics of the device are summarized in table (2).

To generate the control signal $U_{\text{cont}}$, a special form signal generator AKIP-3409/5 is used [8]. The main characteristics of the generator are summarized in table (3).

The error $\delta_f$ of the frequency $f_I$ of the output current $I$ will be calculated using the formula:

$$\delta_f = \frac{|f_{\text{meas}} - f_{\text{cont}}|}{f_{\text{cont}}} \cdot 100\%,$$

where $f_{\text{meas}}$ is the measured value of the frequency $f_I$ of the output current $I$; $f_{\text{cont}}$ – set value of frequency $f_I$ of output current $I$, $f_{\text{Mcont}}$ – maximum set value of frequency $f_I$ of output current $I$.

The experiment is carried out for frequencies $f_{\text{cont}} = 1; 10; 20; 30; 40; 50; 60; 70; 80; 90; 100$ kHz. The number of experimental experiments was 11 repeated experiments. The diagram and appearance of the experimental stand are presented in Figure 6.
The results of assessing the error $\delta_f$ of the frequency $f_i$ of the output current $I$ are presented in Figure 7. The figure shows the arithmetic mean value of the error $\delta_f$ for each value of the frequency $f_i$ of the output current $I$ indicating the standard deviation.

![Fig.7. Estimation of error $\delta_f$ frequency $f_i$ of output current $I$](image)

As can be seen from Figure 7, the maximum relative error $\delta_f$ of the frequency $f_i$ of the output current $I$ does not exceed 0.07%. Starting from frequency $f_i = 8$ kHz error $\delta_f$ does not exceed 0.001%.

To experimentally estimate the error $\delta_I$ of the amplitude $I_m$ output current $I$ we will estimate the amplitude $I_m$ current $I$ through the reference load $R_{load}$. The resistance store P4831 [9] is used as the load $R_{load}$. Load resistance $R_{load} = 50; 100; 500; 1000; 1500; 2000$ Ohm. The main technical characteristics of the resistance store are presented in table (4). To measure the amplitude $I_m$ of the current $I_{load}$, a universal voltmeter AKIP-2101 is used [10]. The main characteristics of current measurement with the AKIP-2101 voltmeter are summarized in table (5).

The AKIP-2101 voltmeter allows you to measure the effective $I_{RMS}$ value [10] of the current, taking into account the signal shape and distortion (True RMS). The amplitude $I_m$ value is calculated using the formula:

$$I_m = I_{RMS} \cdot \sqrt{2},$$

where $I_m$ is the amplitude of alternating current; $I_{RMS}$ – effective value of alternating current.

Calculation of the error $\delta_I$ of the amplitude $I_m$ output current $I$ will be produced according to the formula:

$$\delta_I = \frac{|I_{m,meas} - I_m|}{I_M} \cdot 100\%,$$

where $I_{m,meas}$ is the measured value $\delta_I$ of the amplitude $I_m$ output current $I$; $I_m$ – specified value $\delta_I$ of the amplitude $I_m$ output current $I$; $I_M$ – maximum specified value $\delta_I$ of amplitude $I_m$ output current $I$.

The experiment is carried out for frequencies $f_{cont} = 1; 10; 20; 30; 40; 50; 60; 70; 80; 90; 100$ kHz and amplitudes $I_m = 1; 2; 3; 4; 5$ mA. The number of experimental experiments was 11 repeated experiments. The diagram and appearance of the experimental stand are presented in Figure 8.
After calculating the error values $\delta_I$ for each series of repeated experiments, the arithmetic mean value of the error $\delta_I$ was calculated and processing was carried out similar to the processing of the simulation results. Estimation of the spread of error values $\delta_I$ of amplitude $I_m$ output current $I$ depending on the load resistance $R_{load}$ is presented in the form of a Box-Whiskers diagram in Figure (9). The diagram was built using the Statistica package.

Estimation of the spread of error values $\delta_I$ for different values of $R_{load}$ and $f_{cont}$ is also presented in the form of a Box-Whiskers diagram. As can be seen from Figure 9, as the value of the load resistance $R_{load}$ increases, the error $\delta_I$ of the amplitude $I_m$ increases output current $I$. This is caused by the influence of the load on the current-generating circuit. With increasing frequency $f_{cont}$ of the control signal $U_{cont}$, the error $\delta_I$ of the amplitude $I_m$ output current $I$ also increases, but the influence of frequency $f_{cont}$ is significantly less than the influence of the resistance value $R_{load}$. The influence of frequency in the experiment is more obvious than in the simulation. According to the experimental results, the error $\delta_I$ of the amplitude $I_m$ output current $I$ does not exceed 5% at resistance values $R_{load} = 50..500$ Ohm and frequency $f_{cont} = 1..50$ kHz. With load resistance $R_{load} = 1$ kOhm and frequency $f_{cont} = 1..30$ kHz, amplitude error $\delta_I$ of $I_m$ output current $I$ does not exceed 5%. With load resistance $R_{load} = 1.5$ kOhm and frequency $f_{cont} = 1..10$ kHz error $\delta_I$ amplitude $I_m$ output current $I$ does not exceed 5%.

The human forearm was also used as a load. To do this, using a special medical belt, two rheographic electrodes were attached approximately in the middle of the forearm. The electrodes were located diametrically opposite. The appearance of the CS connection to the
BO is shown in Figure 10. To improve contact between the electrodes and the skin, pieces of fabric moistened with water were placed. The experiment is carried out for frequencies $f_{\text{cont}} = 1; 10; 20; 30; 40; 50; 60; 70; 80; 90; 100$ kHz and amplitudes $I_m = 1; 2; 3; 4; 5$ mA.

Fig. 10. Appearance of CS connection to BO

Figure (11) shows a graph of the error $\delta_I$ versus frequency $f_{\text{cont}}$ control signal $U_{\text{cont}}$ at different amplitudes $I_m$ of current $I$ when using a biological object as a load.

![Graph showing error $\delta_I$ vs. frequency $f_{\text{cont}}$ for different amplitudes $I_m$.]

Fig. 11. Results of calculating the error $\delta_I$

As can be seen from Figure (11), at low frequencies the resistance exceeds 2 kOhm, which does not allow the CS to deliver the required current. The highest accuracy was achieved with amplitude $I_m = 5$ mA and frequency 10 kHz. Error $\delta_I$ of amplitude $I_m$ output current $I$ does not exceed 5% frequency $f_{\text{cont}} = 10..30$ kHz.

6 Conclusion

As a result of the work, an CS injected current source for the EIT device was developed, assembled and investigated. This current source is controlled by voltage and allows you to pass through a grounded load $R_{\text{load}}$ up to 2 kOhm a current with an amplitude $I_m$ of up to 5 mA.
mA. Study of the error δ_I of the amplitude I_m output current I and error δ_f frequency f_cont output current I was produced on a mathematical model and during a full-scale experiment. Active resistance and a biological object were used as the load R_load. As a result of the simulation, it was established that the error δ_I of the amplitude I_m output current I does not exceed 1% at resistance values R_load = 50..100 Ohm and frequency f_cont = 1..100 kHz. With load resistance R_load = 0.5..1 kOhm and frequency f_cont = 1..100 kHz error δ_I amplitude I_m output current I does not exceed 5%. As a result of a full-scale experiment, it was established that when using active resistance as a load R_load the error δ_I of the amplitude I_m output current I did not exceed 5% at resistance values R_load = 50..500 Ohm and frequency f_cont = 1..50 kHz. With load resistance R_load = 1 kOhm and frequency f_cont = 1..30 kHz error δ_I amplitude I_m output current I does not exceed 5%. With load resistance R_load = 1.5 kOhm and frequency f_cont = 1..10 kHz error δ_I amplitude I_m output current I does not exceed 5%. However, this error can be compensated by changing the amplitude U_m control voltage U_cont. To do this, it is necessary to introduce an exemplary resistance into the load circuit and measure the voltage drop across it. Based on the measured data, it is possible to calculate the amplitude value I_m output current I and compensate for the error δ_I. As a result of a full-scale experiment when using a biological object as a load R_load, the amplitude I_m error δ_I of the output current I does not exceed 5% at frequency f_cont = 10..30 kHz.

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