Modeling of a measurement analog channel of a hardware and software system for researching medical electrodes in Matlab

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Abstract. There is an urgent need to improve system design of calibration equipment which allows us to determine parameters and characteristics of medical electrodes. Technical characteristics of a hardware and software system for researching medical electrodes are depending on amplitude–frequency responses of a measurement analog channel. This channel consists of an instrumentation amplifier, a cascaded chain of operational amplifiers including programmable-gain amplifiers and a low-pass filter, therefore calculating amplitude–frequency responses of a measurement channel is a multiparameter problem. This problem can be solved efficiently by simulation with help of Matlab. Simulink-model of a hardware and software system for researching medical electrodes is suggested. The model provides the correct design of a measurement channel. It is subject to design criteria such as accuracy of frequency band and a reduction in gain.

1. Introduction
The most important element of electrophysiological diagnostic systems is a medical electrode intended for measuring biopotentials. There is an urgent need to improve system design of calibration equipment which allows us to determine parameters and characteristics of medical electrodes with high metrological reliability and validity [1].

A hardware and software system for researching medical electrodes (HSSRME) includes a measurement analog channel (AMC) and a digital subsystem being a personal computer [2]. Technical characteristics of HSSRME are regulated by the State Standard GOST 25995-83. Thus, in accordance with this standard, calibration equipment has to have:

1) a frequency band from 0 Hz to 10 kHz ( -3 dB level);
2) a reduction in gain of 12 dB per frequency octave or 40 dB per frequency decade beyond cut-off frequency.

AMC consists of an instrumentation amplifier (in-amp), a voltage follower, a cascaded chain of operational amplifiers (op-amp) including programmable-gain amplifiers and a low-pass filter (LPF). AMC gain takes on values of 5000 and 50000. The cascaded chain of op-amps leads to frequency response distortion.

Determining amplitude–frequency responses of AMC is a multiparameter problem, therefore it is relatively complex. A change in gain of an input in-amp and a type of an output LPF has a great effect on frequency response on condition that AMC gain is equal to 5000 or 50000. This problem can be solved efficiently by simulation of AMC with help of numerical computing environment Matlab. This
software allows plotting of functions and determination of dynamic characteristics and it has an additional package, Simulink, providing a graphical programming tool [3].

2. Design of AMC Simulink-model
The AMC basis is op-amps and an in-amp. The Simulink-models of amplifiers are presented in figure 1.

The op-amp model (figure 1,a) is based on the suggested method [4].

![Simulink-model of an operational amplifier](image)

**Figure 1.** Simulink-model of an operational (a) and instrumentation (b) amplifier.

The amplifier input consists of differential input impedance \( R_1 \) connected to input physical modeling connection ports 1, 2 specified «+In» and «-In» respectively. The output part is connected to “Out” port 3 and comprise of several blocks such as Voltage Sensor, Transfer Fcn, Saturation, Voltage Source, \( R_2 \). The coupling between input and output parts is achieved by Voltage-Controlled Voltage Source with gain \( A_V \). The input part also includes common-mode input impedances \( R_2, R_3 \) for more precise definition of the model. The transfer function is written as:

\[
F = \frac{1}{\frac{A_V}{2\pi f_1} s + 1},
\]

where \( A_V \) – signal differential voltage amplification; \( f_1 \) – unity-gain bandwidth.

Block Saturation limits output voltage according to the supply voltage. Blocks such as Voltage-Controlled Voltage Source, Voltage Sensor (based on PS-Simulink Converter and Voltage Sensor) and Voltage Source (based on Simulink-PS Converter and Controlled Voltage Source) are necessary for converting an input Simulink signal into a Simscape signal, and conversely.

In-amp model (figure 1,b) consists of an input gain block and a first-order LPF. Simulink-model is implemented by block Gain setting the gain and block Analog Filter Design implementing the first order Butterworth filter.

To meet the requirements of State Standard GOST 25995-83, LPF has to have at least second order, but it has the slope being less than -12 dB per octave near the cut-off frequency. Therefore a higher order of LPF is used to increase falling edge steepness (figure 2).

The model comprises two op-amps \( DA_1, DA_2 \) (integrated circuit TLE2027), capacitors \( C_1-C_3 \) and resistors \( R_5-R_7 \). Different types of LPF were used in the simulation: low-pass filter with critical damping, Bessel low-pass filter, Butterworth low-pass filter. The parameters of LPF were determined by the method suggested in [5].
Integrated circuit AD8422 is used as an input in-amp DA3 in AMC (figure 3). AD8422 has small signal −3 dB bandwidth $f_c=850$ kHz at a gain of 10 ($A_{DA3}=10$), $f_c=120$ kHz at $A_{DA3}=100$, $f_c=12$ kHz at $A_{DA3}=1000$ according to the datasheet [6].

Amplifier DA5 is based on integrated circuit ADA4077-1 and has constant gain $A_{DA5}=5$ which is set by resistors $R_8$, $R_9$. The same goes for amplifier DA7 (TLE2027) with gain $A_{DA7}=-1$ and for amplifier DA4 (TLE2027) with gain $A_{DA4}=1$. Programmable-gain amplifier DA6 (TLE2027) is controlled by discrete changing in $R_{12}$ resistance at constant value of $R_{10}$. Block DA8 implementing the third order LPF (figure 2). Voltage Sensor and Voltage Source convert the input Simulink signal into a Simscape signal, and conversely. The Simscape block diagram requires exactly one Solver Configuration block to specify the solver parameters.

Table 1 shows the amplifiers gains of AMC for different scale ranges – 0.2 mV and 2 mV. There are three options of setting AMC gain for each scale range. For example, the second row is calculated from the equation: $|A_{AMC}| = A_{DA3} \cdot |A_{DA7}| \cdot A_{DA5} \cdot A_{DA6} = 1000 \cdot 1 \cdot 5 \cdot 10 = 50000$. 

![Figure 2. Simulink-model of third-Order Low-Pass Filter.](image1.png)

![Figure 3. Simulink-model of measurement analog channel.](image2.png)
3. Simulation

The AMC model was simulated with various types of LPF and different gains of the measurement channel. The purpose of experiments is to determine AMC cut-off frequency. Accuracy of cut-off frequency can be calculated by the relation:

$$\varepsilon = \left| \frac{f_{mf} - f_{ef}}{f_{ef}} \right| \cdot 100\%,$$

where $f_{mf}$ – measured frequency at the -3 dB level, $f_{ef}$ – cut-off frequency being equal to 10 kHz.

Results of simulation are shown in Table 2. From the latter it follows that the least error in cut-off frequency was for $A_{DA3}=100$ regardless of LPF type. Notably, LPF with critical damping has accuracy of 0.48% and 0.07% at $A_{AMC}=5000$ and 50000 respectively, Bessel LPF – 0.14% and 0.21%, Butterworth LPF – 0.34% and 0.48%. However, for $A_{DA3}=100$ accuracy is the lowest (from 15.98% for Butterworth LPF to 26.67% for LPF with critical damping), because of AD8422 bandwidth narrows down to 12 kHz as the in-amp gain increases up to 1000. In addition, op-amp $DA6$ gain have to be equal to 1000 due to the need to set $A_{AMC}=50000$ and $A_{DA3}=10$ (table 1). It leads to bandwidth narrowing of AMC. In this case cut-off frequency accuracy ranges from 14.10% for Butterworth LPF to 24.04% for LPF with critical damping.

### Table 1. Voltage gain of the AMC amplifiers.

| No  | $A_{DA3}$ | $|A_{DA7}|$ | $A_{DA5}$ | $A_{DA6}$ | $A_{AMC}$ | Scale range, mV |
|-----|-----------|------------|-----------|-----------|-----------|-----------------|
| 1   | 1000      | 1          | 5         | 10        | 5000      | 2               |
| 2   | 1000      | 1          | 5         | 10        | 50000     | 0.2             |
| 3   | 100       | 1          | 5         | 10        | 5000      | 2               |
| 4   | 100       | 1          | 5         | 10        | 50000     | 0.2             |
| 5   | 10        | 1          | 5         | 10        | 5000      | 2               |
| 6   | 10        | 1          | 5         | 1000      | 50000     | 0.2             |

### Table 2. Accuracy of Simulink-model cut-off frequency.

| Filter type | $A_{DA3}$ | $|A_{DA7}|$ | Cut-off frequency, Hz | Accuracy, % | Cut-off frequency, Hz | Accuracy, % |
|-------------|-----------|------------|-----------------------|-------------|-----------------------|-------------|
| Low-pass filter with critical damping | 10 | 10062 | 10048 | 7333 | 2.67 | 7596 | 24.04 |
|             | 100       | 10048     | 10004 | 7333 | 26.67 | 7596 | 24.04 |
|             | 1000      | 7333      | 26.67 | 7596 | 24.04 | 24.04 |
| Bessel low-pass filter | 10 | 10021 | 10014 | 7533 | 24.67 | 7533 | 24.67 |
|             | 100       | 10014     | 10006 | 7533 | 24.67 | 7533 | 24.67 |
|             | 1000      | 7533      | 24.67 | 7533 | 24.67 | 24.67 |
| Butterworth low-pass filter | 10 | 9972 | 9966 | 8402 | 15.98 | 8402 | 15.98 |
|             | 100       | 9966      | 9952 | 8402 | 15.98 | 8402 | 15.98 |
|             | 1000      | 8402      | 15.98 | 8402 | 15.98 | 15.98 |

Another metric of choice is a reduction in gain beyond cut-off frequency. AMC frequency response with $A_{DA3}=100$ was simulated in Matlab. Results are shown in figure 4.
Figure 4. Amplitude–frequency responses of AMC ($A_{AMC}=5000$, $A_{DA3}=100$).

The relationship between frequencies at -5 dB and frequency at -17 dB can be obtained directly from figure 4. The ratio is 2.2 for AMC with LPF with critical damping. It does not meet the requirement for a reduction in gain of 12 dB per frequency octave. The Bessel and Butterworth LPF satisfy the requirement for a reduction in gain. The Bessel filter has the least error in cut-off frequency, therefore it was chosen in the practical implementation of AMC.

4. Conclusion

The suggested AMC Simulink-model is subject to design criteria such as accuracy of frequency band and a reduction in gain of 12 dB per frequency octave. The model provides the correct design of a hardware and software system for researching medical electrodes.

References

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