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The Effect of Inaccurate Electronic Component Values on The Output Frequency Characteristics of Fourth Order Butterworth Type Low-pass Filter Circuits

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ABSTRACT

The low-pass filter op-amp circuit is an active electronic circuit used to pass low frequencies. In practice, making this circuit requires active components in the form of an operational amplifier and several passive components such as resistors and capacitors. To obtain the required passive component values, calculations are carried out according to theory, but the results of these calculations sometimes make it difficult for users to find the values for the same components. Components sold on the market do not always exactly match the user's needs, so sometimes these components are replaced with components whose size is close to the calculated value. Therefore, in this research, testing was carried out regarding the effect of inaccurate component values on the filter output characteristics. From the results of this research, it was found that the cut-off frequency decreased by 6.25% and that premature damping occurred at low frequencies at 100 Hz. However, overall this series of filters is still suitable for use.

1. INTRODUCTION

To eliminate electronic signal noise, we can use an active filter in the form of an op-amp feedback circuit using resistor and capacitor components. There are three general types of configurations for using Op-Amps as filters, namely lowpass filters, high-pass filters and bandpass filters. High-pass Filter is a filter or frequency filter that can pass high frequency signals and inhibit or block low frequency signals. In other words, high frequency signals will more easily pass through the High-pass Filter while low frequency signals will be inhibited or difficult to pass through. The ideal High-pass Filter that does not pass signals with frequencies below the cut-off frequency at all (Trisnawati, 2021). While low-pass filters have the ability to pass frequencies below the cut-off frequency, several filters are also used in audio signal processing, especially to remove background noise (Tun & Swe, 2020). In eliminating noise, especially in audio signals, there are other methods such as Noise Cancellation, which utilizes an inverting signal from audio noise to oppose the original noise signal so that there is a weakening of the amplitude due to the signals being in opposite phase by 180 degrees (Chaki, 2021).

Techniques for making op-amp-based active filters usually apply a Sallen-Key circuit topology. This classic filter design utilizes op-amps and passive components such as resistors and capacitors to pass the desired frequency (Denisenko et al., 2022). Sallen-Key topology is usually followed by mathematical calculations to determine the value of components such as resistors and capacitors needed. In this calculation, there are three optimization methods to obtain the expected frequency cut-off point, namely Butterworth, Chebyshev and Bessel (Mancini, 2003). The Butterworth method has the advantage of a flat signal response in the passband area compared to other methods, although the other methods have different characteristics, Butterworth is a method with a cut-off character that is in the middle of the others (Thompson, 2014). Filters using the Butterworth method have passband amplitude response characteristics that are almost flat and have no ripples, so they are relatively better than Chebyshev filters, which are also commonly used filter designs (Laghari et al., 2014; Paarmann, 2001).

Even though it is relatively easy, making a Butterworth filter is not without problems. In general, when building a filter using this method, you must pay attention to the value of the components used. Problems arise when the value of the component that we will use is not sold on the market, especially the value of the capacitor that will be used, so it requires us to make a series and parallel circuit to get the desired value. However, does this mismatch in capacitor values have a significant impact on the expected output results? Therefore, in this research, will identify the effect of inaccurate component values on the frequency output characteristics of a low-pass filter circuit using the Butterworth method.

2. METHOD

In this research, a fourth order Butterworth type low-pass filter op-amp circuit was built. The cut-off frequency is 400 Hz, so frequencies more than the cut-off frequency will be attenuated. The research begins by designing the circuit that will be used and then testing the circuit by providing variations in frequency input. Details of the design and testing methods are explained in the following subsections.

2.1 Fourth Order Butterworth Filter Design

To make an op-amp-based filter, calculations are needed to determine the value of the components needed in the circuit (Blackledget, 2006). In this research, it was determined that a fourth order filter was made, so that according to Figure 1, the number of op-amps used was two. The op-amp circuit design follows the Sallen-Key topology where this circuit utilizes a feedback capacitor between the non-inverting input and the op-amp output (Self, 2011). This design uses a unity amplifier, which means that the input signal amplitude is the same as the output (Jankowski & Napieralski, 2013). Figure 2 shows the circuit of the Fourth Order Butterworth filter used in this research.

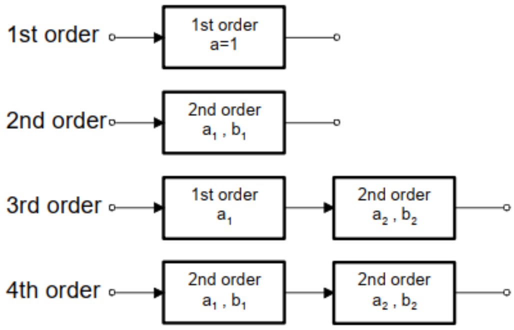

Figure 1. Multilevel Filter Stages for High-Level Filters

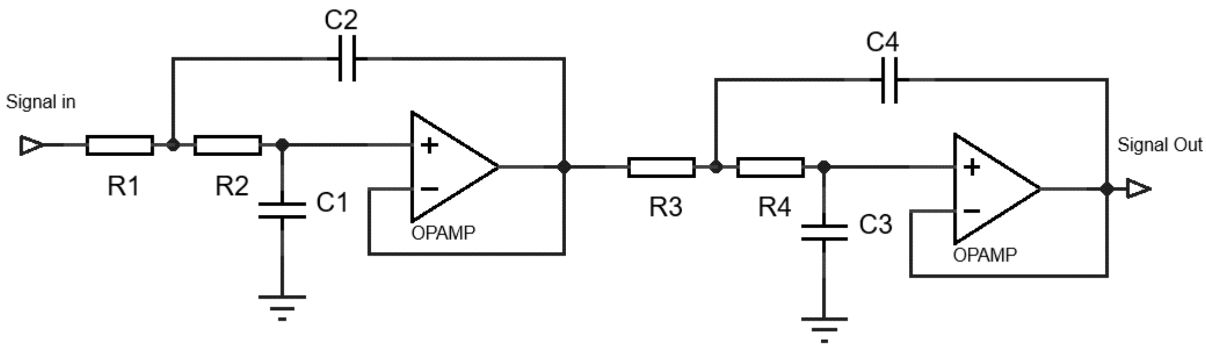

Figure 2. Fourth Order Sallen-Key Butterworth Filter

The value of the capacitor used is calculated using the equation,

$$C_2 \geq C_1 \frac{4b_2}{{a_2}^2} \qquad (1)$$

We can determine the value of the capacitor C_1 ourselves, then enter this value into Equation (1) to obtain the value of C_1 from the calculation results.

The next step is to carry out calculations using Equations (2) and (3) to obtain large values for R_1 and R_1. The f_c parameter is determined by 400 Hz which is the cutoff frequency of the designed lowpass filter. Meanwhile, the values a_1 and b_1 are the Butterworth coefficient values based on Table 1.

$$R_1 = \frac{a_1C_2 - \sqrt{{a_1}^2{C_2}^2 - 4b_1C_1C_2}}{4\pi f_c C_1 C_2} \qquad (2)$$

$$R_2 = \frac{a_1C_2 - \sqrt{{a_1}^2{C_2}^2 - 4b_1C_1C_2}}{4\pi f_c C_1 C_2} \qquad (3)$$

Table 1. Butterworth coefficient values up to fourth order

n	i	a_i	b_i
1	1	1.0000	0.0000
2	1	1.4142	1.0000
3	1	1.0000	0.0000
	2	1.0000	1.0000
4	1	1.8478	1.0000
	2	0.7654	1.0000

In the fourth order filter, based on Figure 2, there are two stages of the filter circuit. To calculate the values for $R_3, R_4, C_3, and C_4$, you only need to recalculate by adjusting the Butterworth coefficient for the second level value (Mancini, 2003).

2.2 Test Simulation

Before the entire circuit is built, it is necessary to test it in a computer simulation to ensure that the calculations carried out are in accordance with the expected results. In this research, PSpice simulation software was used to analyze the Butterworth lowpass filter electronic circuit according to Figure 1, using component values that had been previously calculated. Later the output from this simulation will be a graph between the frequency and the resulting signal gain in dB units. The design built can be said to be suitable if the simulation graph of test results shows a value of – 3 dB when the signal is at a frequency of 400 Hz.

2.3 Filter Construction and Testing

When the simulation testing is appropriate, then proceed with building a filter circuit with components according to the design. For the op-amp, in this study the UA741 type op-amp was used because it works quite well in the frequency range up to 10k Hz. Meanwhile, the thing you need to pay attention to is the value of the components used, because each passive component must have a tolerance value, which means the actual value can be greater or higher for both resistors and capacitors.

It is the imperfection of this component that will be looked at in this research, whether it will have a significant impact on the characteristics of the lowpass filter being built. To get component values that are close to the actual value, in practice the components will be connected in series or parallel.

3. RESULTS AND DISCUSSION

3.1 Simulation Result

After carrying out calculations using equations 1, 2 and 3, the resistor and capacitor component values are obtained from $R_1 = 3674\,\Omega, R2 = 3674\Omega, R3 = 1522\Omega, R4 = 1522\Omega$, then the capacitor value $C_1 = 100$, $C_2 = 117\,nF$, $C_3 = 100\,nF$, $C_4 = 683\,nF$. This component is then inserted into the circuit simulation in Figure 1, so that a comparison graph between frequency and signal gain is obtained as in Figure 3.

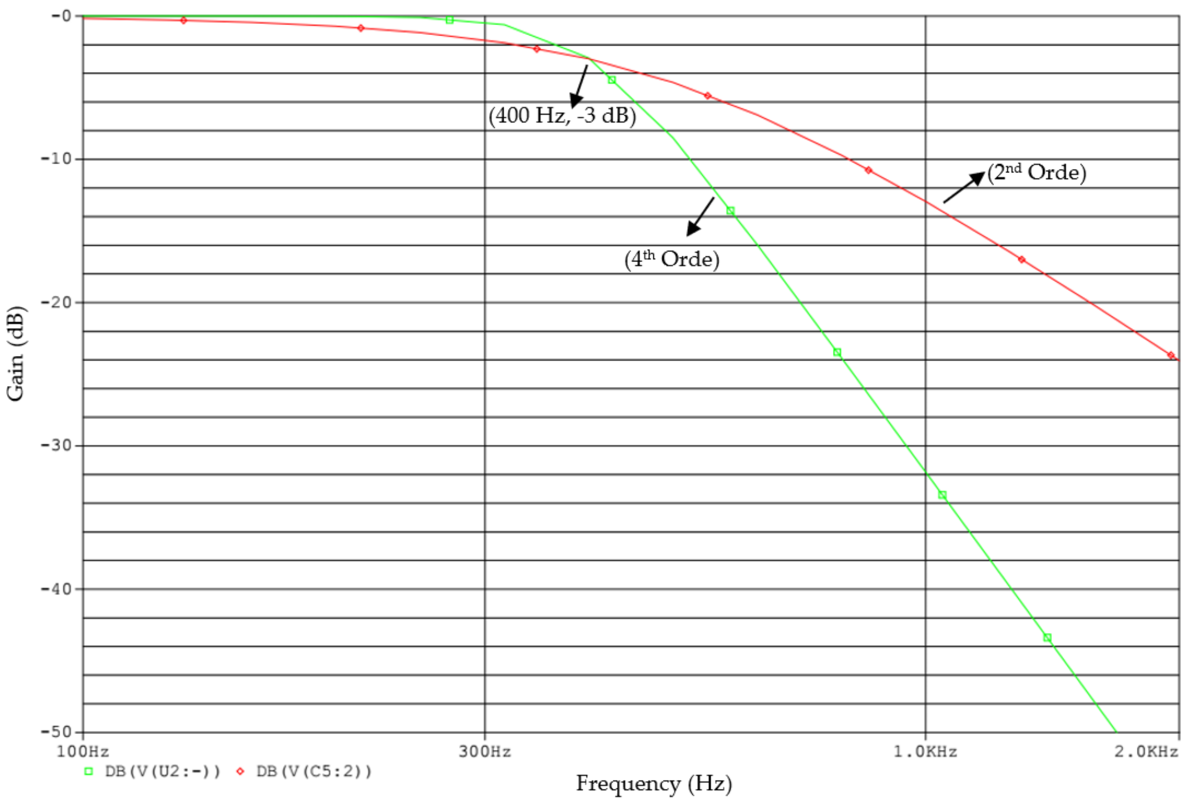

Figure 3 Comparison of second-order and fourth-order low-pass filter simulation results

The red line is the frequency characteristic pattern of the second order lowpass filter, while the green line is the frequency characteristic pattern of the fourth order lowpass filter. It can be observed that, these two orders have an appropriate cut-off point according to the design, namely 400 Hz at -3 dB. The fourth order filter has better gain stability than the second order, this is proven by the fourth order gain graph which tends to be stable when the frequency is 100 Hz to 300 Hz, while in the second order the gain has started to decrease since the frequency is 100 Hz. Moreover, as the frequency increases, the gain graph drops sharply, indicating that the output signal can be well attenuated by the low-pass filter circuit.

Based on Figure 3, it can be seen that at 400 Hz the filter output signal experiences a decrease of -3 dB, this is in accordance with the theory that the low-pass cut-off frequency of the Butterworth filter is -3 dB (Mancini, 2003). Therefore, this filter design is computationally appropriate and can be continued to build filter hardware.

3.2 Hardware Output Results

The resistor value approach from the calculation results used in this low-pass filter hardware is as follows, $R_1 = 3674\ \Omega$, $R2 = 3674\Omega$, $R3 = 1522\Omega$, $R4 = 1522\Omega$. The resistor used has the same value as the calculation result, this is due to the use of a variable resistor in the circuit so that the resistance value can be adjusted according to needs. For the capacitor values selected as follows $C_1 = 97$ nF, $C_2 = 120$ nF, $C_3 = 96$ nF, $C_4 = 708$ nF. The average percentage discrepancy in capacitor values in this circuit is around 3.3%, which can be said to be a very small difference between the capacitor values used and those simulated.

The circuit that has been built can be seen in Figure 4, this circuit uses two uA741 op-amps, this type of op-amp was chosen because its working frequency is up to 1 MHz so it is sufficient to analyze signals with a predetermined cut-off frequency of 400 Hz. Tantalum type capacitors (yellow components) are used in this device, this is because this type of capacitor is known to have high stability compared to other types of capacitors (Freeman et al., 2021). To get an accurate resistor value, a variable resistor (blue box-shaped component) is used, so that the resistance value can be adjusted precisely.

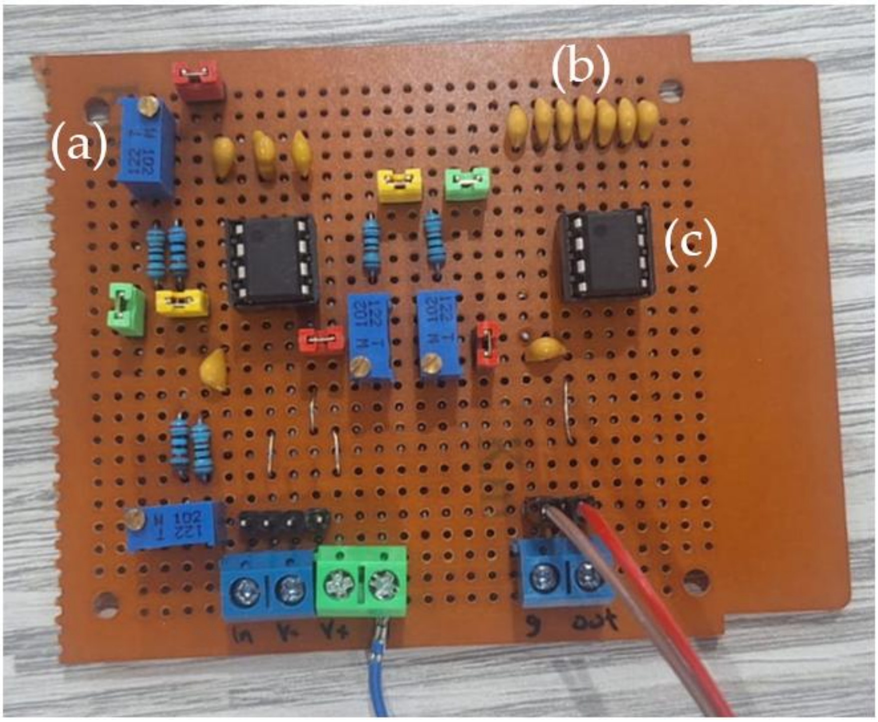

Figure 4. Low-pass filter hardware circuit that has been built. (a) variable resistor;(b) capacitor;(c)op-amp

Based on Figure 5, it can be observed that the graph of the gain characteristics between the simulation and the device being built is very identical. The differences in frequency gain results between the observed systems are not much different. However, due to differences in component values in the capacitor, the cut-off frequency of the circuit changed to 375 Hz or decreased by around 6.25%. At a frequency of 100 Hz, damping begins to occur when compared to the simulation that occurs at a frequency of 300 Hz. Even though there are differences, this circuit is still suitable for use, because the gain graph is still close to the simulation results.

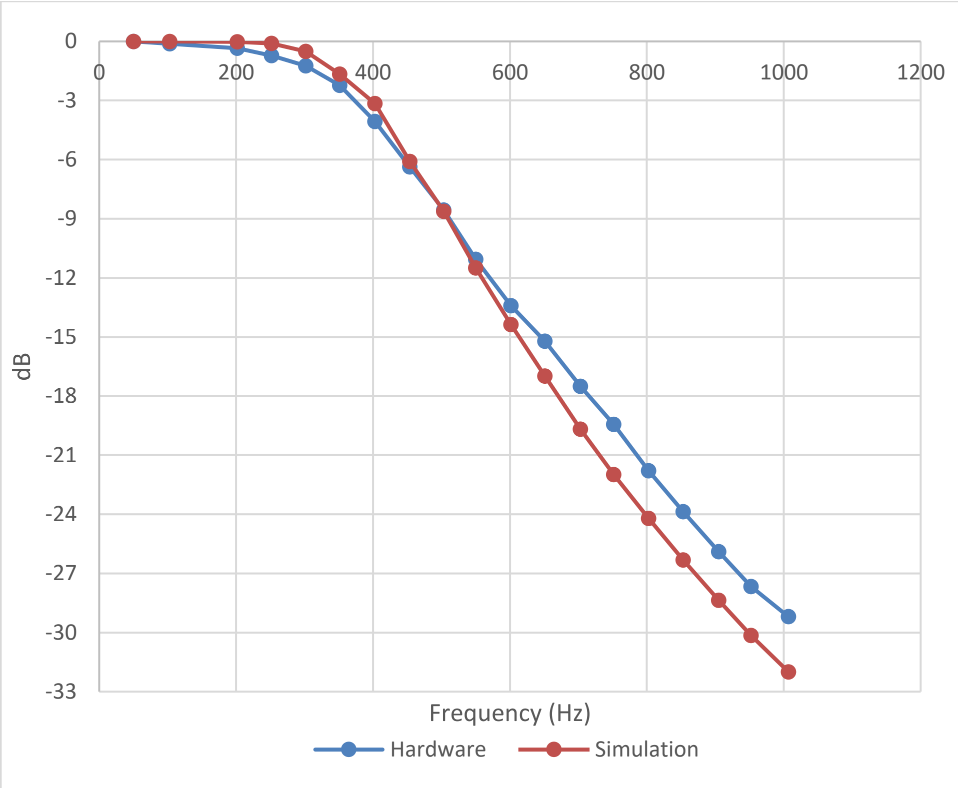

Figure 5. Comparison of filter gain between simulation and built device

4. CONCLUSION

Making a fourth order Butteworth type low-pass filter using imprecise component values does not have much influence on the expected signal characteristics. The effect observed from the inaccuracy of the components used is a decrease in the cut-off frequency of 6.25% due to component errors of around ±3.3%, as well as premature damping at low frequencies starting from 100 Hz. However, the device built is still very suitable for reducing high frequencies, because the characteristic graph is still identical to the simulation results. Therefore, when making op-amp-based filters, as much as possible, keep the component values according to the calculations, so that the damping characteristics of the filter are still relevant to the initial design.

REFERENCE

Blackledget, J. M. (2006). The Fourier Transform. *Digital Signal Processing*, 75–113. https://doi.org/10.1533/9780857099457.1.75

Chaki, B. (2021). Audio noise cancellation using Op-amp. *International Journal of Innovative Research in Technology*, *7*(8), 92–93. https://ijirt.org/Article?manuscript=150625

Denisenko, D., Prokopenko, N., & Bugakova, A. (2022). Low Pass Filter of the Sallen-Key Family with Main Parameters' Independent Adjustment. *Proceedings of 2022 IEEE 16th International Conference on Solid-State and Integrated Circuit Technology, ICSICT 2022*. https://doi.org/10.1109/ICSICT55466.2022.9963174

Freeman, Y., Lessner, P., & Luzinov, I. (2021). Reliability and Failure Mode in Solid Tantalum Capacitors. *ECS Journal of Solid State Science and Technology*, *10*(4), 045007. https://doi.org/10.1149/2162-8777/ABF728

Jankowski, M., & Napieralski, A. (2013). High-voltage high input impedance unity-gain voltage buffer. *Microelectronics Journal*, *44*(7), 576–585. https://doi.org/10.1016/J.MEJO.2013.03.006

Laghari, W. M., Baloch, M. U., Mengal, M. A., Shah, S. J., Laghari, W. M., Baloch, M. U., Mengal, M. A., & Shah, S. J. (2014). Performance Analysis of Analog Butterworth Low Pass Filter as Compared to Chebyshev Type-I Filter, Chebyshev Type-II Filter and Elliptical Filter. *Circuits and Systems*, *5*(9), 209–216. https://doi.org/10.4236/CS.2014.59023

Mancini, Ron. (2003). *Op Amps for Everyone*. 469.

Paarmann, L. D. (2001). *Design and analysis of analog filters : a signal processing perspective* (1st ed., Vol. 1). Kluwer Academic Publishers.

Self, D. (2011). Op-amps for Active Crossovers. *The Design of Active Crossovers*, 369–412. https://doi.org/10.1016/B978-0-240-81738-5.00013-6

Thompson, M. T. (2014). Analog Low-Pass Filters. *Intuitive Analog Circuit Design*, 531–583. https://doi.org/10.1016/B978-0-12-405866-8.00014-0

Trisnawati, F. (2021). HIGH PASS FILTER | Jurnal Repo Teknologi. *Jurnal Repoteknologi*, *1*(3), 1–8. http://repoteknologi.id/index.php/repoteknologi/article/view/68

Tun, P. T. Z., & Swe, K. T. (2020). AUDIO SIGNAL FILTERING WITH LOW-PASS AND HIGH-PASS FILTERS. *International Journal Of All Research Writings*, *2*(12), 1–4. http://www.ijciras.com/Users/ManuScript/ManuScriptDetails/65af9e71-8151-432d-9371-d0fe74f31c29