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# Floating ground - the path for conductive disturbances in active filter circuit

***Streszczenie.*** *W artykule przedstawiono wyniki pomiarów parametrów elektrycznych zaprojektowanego i wykonanego aktywnego filtru pasmowo-przepustowego z wielokrotną pętlą sprzężenia zwrotnego. Szczegółowo opisany został problem sprzężenia zaburzeń przewodzonych poprzez ścieżkę masy z wejściem zastosowanych wzmacniaczy operacyjnych powodujący błędne działanie filtru. Ograniczenie zakłóceń w pracy układu jest możliwe przez zmniejszenie pojemności sprzęgających lub/i zapewnienie odpowiedniego uziemienia.* ***Wyniki pomiarów parametrów elektrycznych zaprojektowanego i wykonanego aktywnego filtru pasmowo-przepustowego z wielokrotną pętlą sprzężenia zwrotnego***

***Abstract****. In the paper the results of measurements of the electrical properties of the multiple feedback band-pass filter are presented. The problem of conductive disturbances coupling by the grounding path with the input of the operational amplifiers is described in detail. The interferences in operation of the circuit may be reduced by decreasing the coupling capacitances and/or ensure proper grounding.*

**Słowa kluczowe**: filtr aktywny, zaburzenia przewodzone, pływające uziemienie, wzmacniacz operacyjny.
**Keywords**: active filter, conductive disturbances, floating ground, op-amp.

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## Introduction

The band-pass filter with adjustable mid-band frequency was designed on the basis of the numerous simulations in PSpice software [1]. It was supposed to filter out odd harmonics of 50Hz in the range of frequencies up to 2kHz. Hence, it was needed to posses extremely high roll-off and relatively small pass-band in order to ensure appropriate attenuation of the previous and the following odd harmonic. Therefore, numerous filter design techniques were taken into account in order to ensure that the best solution will be chosen. Regarding the goals of the project, disadvantages and advantages of each filter type were considered. Finally, it was decided that the fourth order multiple feedback band-pass filter will be constructed.

## Multiple feedback band-pass filter

In order to ensure desired gain as well as the output characteristics of the circuit feedback loop, which consists of resistors and capacitors, is used. The op-amp senses the difference between the voltages applied at the input terminals, amplifies it by open-loop gain A and make the resulting voltage $A(v_2 - v_1)$ to appear at the third terminal. Moreover, operational amplifier requires two DC power supplies to operate properly. In order to ensure linear operation of the operational amplifier, when output signal is linearly proportional to the input signal, the difference between the inverting and non-inverting terminals should be equal to zero [2]. The most important op-amp parameters, which have the most significant impact on the filter performance, are gain bandwidth and slew rate. Gain bandwidth is defined as the op-amp open-loop voltage amplification and the frequency at which it is measured. It should be considerably higher than the highest pass-band signal's frequency, otherwise filter response can be significantly distorted. Slew rate is defined as the average time rate of change of the closed loop amplifier output voltage for a step-signal input. It should be sufficient in order to ensure that the filter does not create signal distortions[3].

The most important of the multiple feedback band-pass filter is the fact that it allows to adjust the quality factor, gain of the amplifier and a centre frequency independently. For a second-order multiple feedback band-pass filter centre frequency can be adjusted with a single resistor. Moreover, gain of the op-amp depends also on only one resistor and it has negligible impact on the centre frequency. Therefore, gain of the op-amp can be adjusted freely. Multiple feedback band-pass filter is a circuit based around negative feedback active filter of a relatively high quality factor and steep roll-off on both sides of the centre frequency.

Schematic diagram of the fourth order multiple feedback band-pass filter is shown in figure 1.

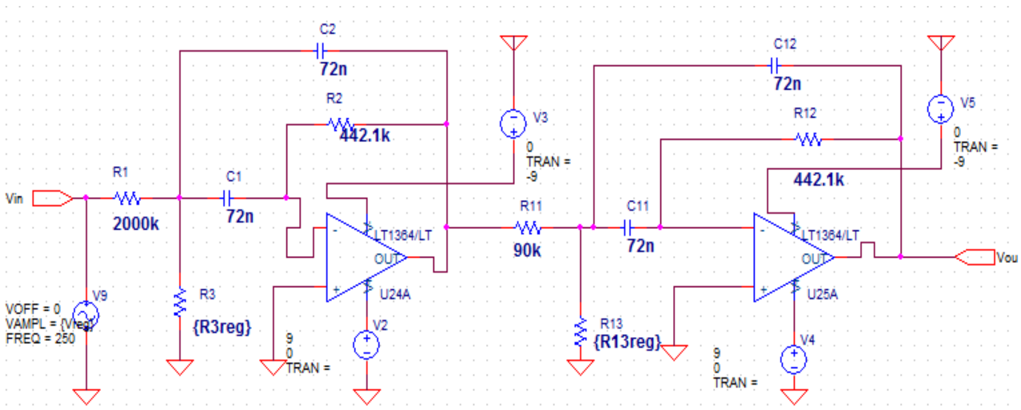


Fig.1. Fourth order multiple feedback band-pass filter

Transfer function of one stage is described by equation [4].

$$\frac{V_{out}}{V_{in}} = \frac{-\frac{R_2 R_3}{R_1 + R_3} C\omega_r s}{1 + \frac{2R_1 R_3}{R_1 + R_3} C\omega_r s + \frac{R_1 R_2 R_3}{R_1 + R_3} C^2 \omega_r^2 s^2} \quad (1)$$

where, $s=j\omega/\omega_r$, $\omega_r$ is a resonant frequency, $R_1$, $R_2$ and $R_3$ are resistances, $C = C_1 = C_2$ is a capacitance.

Both capacitors in figure 1 were decided to be the same as it does not have any impact on the circuit performance, but significantly reduces calculations. As most of the band-pass filters are composed of low-pass and high-pass filters, this one also exhibits those features, components R1 and C2 provide the low-pass response while C1 and R2 provide the high-pass response. Based on equation 1, following design equations can be derived:

(2) $$R_2 = \frac{1}{\pi CBW}$$

(3) $$R_1 = -\frac{R_2}{2A_0}$$

(4) $$R_3 = \frac{R_1}{4\pi^2 C^2 f_r^2 R_1 R_2 - 1}$$

Resistor $R_3$ is the component being switched to adjust the centre frequency of the circuit. In order to design the filter, its pass-band bandwidth had to be chosen first. Afterwards, the capacitance should be selected. It has crucial impact on the circuit design as it decides the range of resistor values. It should be noticed that increase of the capacitance causes the decrease of resistance. In that case loading on the input buffer of the operational amplifier should be maintained on the reasonable level. On the other hand, low values of capacitance may cause issues with a stray capacitance and resistor values becoming too high [5]. Therefore, after numerous computations performed in PSpice software, it was set to 72nF. In order to ensure desired attenuation of the undesired harmonics of the input signal it was decided that two stages of the multiple band-pass filter need to be cascaded. Although, only the resistor $R_1$ at the first stage of the filter was responsible for the adjustments of an output signal's amplitude.

Operational amplifier that was selected to fulfil objectives of the project is LT1364. It is a voltage feedback amplifier with high slew rate being equal to 1000V/μs. Moreover, its bandwidth product is equal to 70MHz, which seemed to be more than sufficient to meet the requirements of the task [6]. It was supplied with two batteries of the voltage being equal to ±9V and input voltage was allowed to be in same range. At first the circuit was experiencing heavy distortions at the output terminal and was easily getting excited resulting in inability of the circuit to operate efficiently. In order to deal with that issues the bypass capacitors were placed at the output of each stage of the circuit as well as between the circuit and batteries. It was done as power supply might often supply an AC signal superimposed on the DC line while a bypass capacitor can decouple a subcircuit from those AC signals [7, 8]. Simulated in PSpice software transfer function of the fourth-order multiple feedback band-pass filter (Fig.1), illustrated for the first and second ten centre frequencies, are presented in figures 2 and 3.

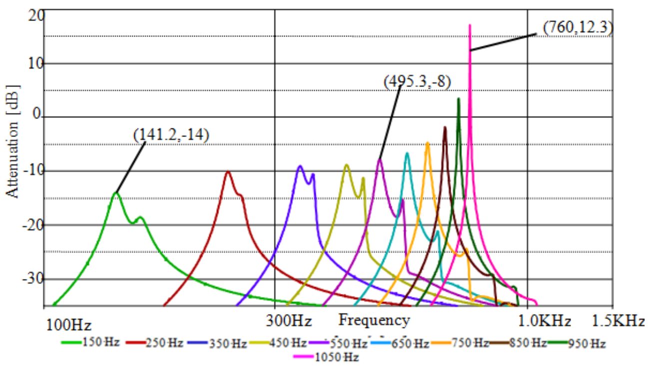


Fig.2. Transfer function of the fourth-order multiple feedback band-pass filter, illustrated for the first ten centre frequencies with usage of a real model of an operational amplifier LT1364

Firstly, it can be noticed that the transfer function is increasing up to the frequency which should be situated at 1050Hz but in fact can be found at 760Hz. Since, output signal was desired to be at the same amplitude level, consecutive resistor $R_1$ and $R_{11}$ had to be adjusted.

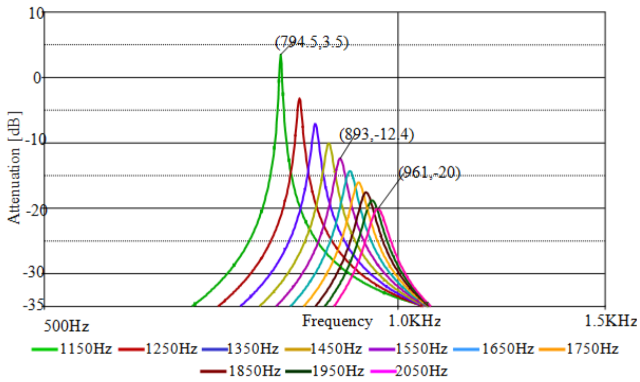


Fig.3. Transfer function of the fourth-order multiple feedback band-pass filter, illustrated for the second ten centre frequencies with usage of a real model of an operational amplifier LT1364

The most interesting issue can be noticed for higher frequencies, above 760Hz. It can be seen that the transfer function starts to decrease, which may indicate that the operational amplifier begins to have difficulties with handling higher frequencies. Furthermore, it can be observed that centre frequency, which should be situated at 550Hz, can actually be found at 495Hz while using LT1364 operational amplifier. As it was said, this effect is getting more significant for higher frequencies, for instance, centre frequency ideally situated at 1050Hz can be found at 760Hz. Furthermore, second ten centre frequencies are spread in the range of 200Hz, while ideally they should take the bandwidth of 1kHz. Therefore, it became impossible to reach the harmonics greater than 950Hz using this configuration. Mainly it was caused by the fact that in this configuration, resistor values are becoming extremely small compared to the other resistors present in the circuit. It is a direct consequence of the equation 4 as it can be noticed there that resistor $R_3$ is inversely proportional to the square of the centre frequency.

## Results of measurements

Results of the measurements are presented in figures 4, 5 and 6.

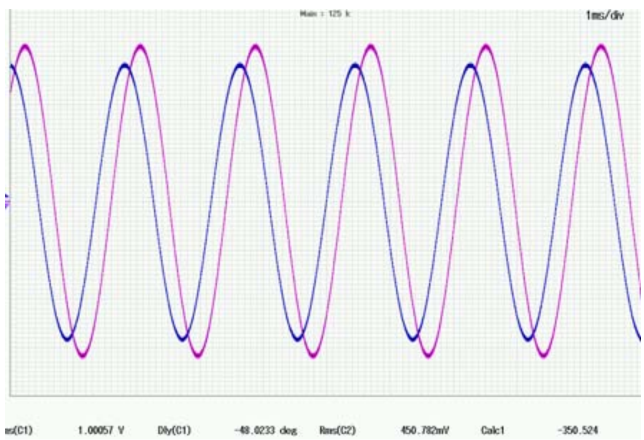


Fig.4. Waveforms of the output signal multiplied by ten (higher amplitude value) and input signal (smaller amplitude value) having an amplitude of $V_{RMS}$=1V for a frequency equal 550Hz

Signal generator was set to 550Hz and the circuit was set to filter out the signal of 550Hz. The amplitude of the input signal was taking various values, staring with 1V (Fig. 4), followed by 5V (Fig. 5) and finally 7V (Fig. 6). Amplitude of 7V was the highest one as it was the highest value, which could be obtained utilizing a generator present in the laboratory. Input signal is connected to channel 1 and is marked as an blue line whereas the output signal is connected to channel 2 and is marked as a violet line. At the bottom of all figures, following parameters can be seen. From the left, a root mean square value of a voltage at the input of the circuit, second one is the phase shift between channels, it is followed by the rms value of the output signal and finally the percentage difference of the output signal in relation to the input voltage *calc1* computed using equation:

(5)
$$calc1 = \frac{V_{INRMS} - 10V_{OUTRMS}}{V_{INRMS}} \cdot 100\%$$

Ideally it should be equal to zero, however the circuit was designed to keep it below 0.2%.

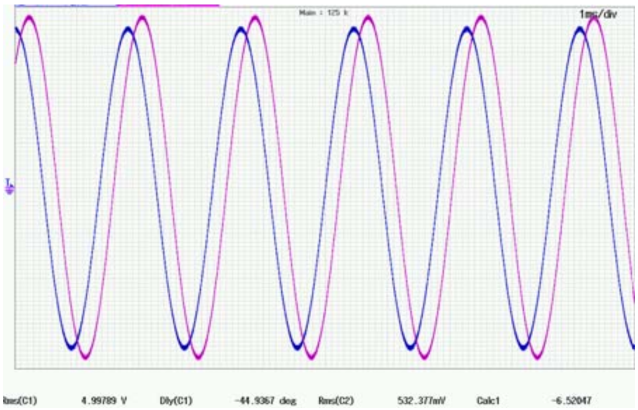


Fig.5. Waveforms of the output signal multiplied by ten (higher amplitude value) and input signal (smaller amplitude value) having an amplitude of $V_{RMS}$=5V for a frequency equal 550Hz

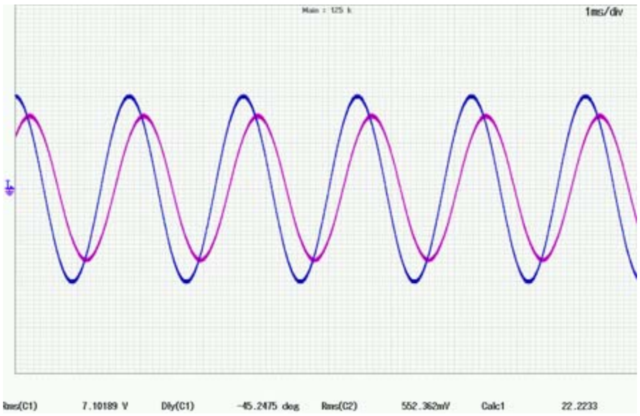


Fig.6. Waveforms of the output signal multiplied by ten (smaller amplitude value) and input signal (higher amplitude value) having an amplitude of $V_{RMS}$=7V for a frequency equal 550Hz

At first it should be mentioned that the amplitude of the output signal was supposed to be ten times smaller than the input signal. Moreover, during the construction of the circuit, it was adjusted for the input signal of 5V. In figures presented above it might be noticed that the percentage difference is widely spread for the consecutive amplitudes of the input signal. The percentage difference is equal to 350.5% for an input signal being equal to 1V, while for input of 7V it can be found to be equal to 22.2%. It can be also seen that the smallest percentage difference occurs for the signal slightly higher than 5V since the amplitude of the output signal was adjusted for the input signal of 5V with the assumption that the circuit will work linearly. Moreover the output signal approaches the desired value of 500mV for every value of input signal's amplitude. Therefore on the basis of the presented measurements, it can be concluded that the voltage harmonic of the designed filter mid-band frequency was filtered out from distorted input voltage but its value was always approaching the maximum output voltage of the designed filter independently from the value of the input voltage. Hence, it can be said that the circuit operates non-linearly.

**Discussion of the results**

Non-linearity of the circuit is intensifying for higher amplitude of an input signal as well as higher frequencies. Moreover, the circuit seemed to work linearly for the frequencies up to 150Hz and the amplitude of an input signal of 3.6V. After taking closer look to the cause of the non-linear operation of the filter, it appeared that capacitors placed at the output of each op-amp were the main cause of an issue. As it was said they fixed the issue of heavy distortions at first, however, it was probably a short term solution. Their impact on the linearity of the circuit was not spotted on the simulation because of the ideal zero ground exploited over there. While in constructed circuit it is a reference point from which the signal is measured. It was about the fact that the low-level signal, which in that case was non-inverting terminal of an op-amp, was connected to the same grounding point as the high-level signal, which in that case was capacitor placed at the output of an op-amp. It led to mixing of those signals and variation in the voltage at the non-inverting terminal, which resulted in operation of the op-amp in the non-linear region. This is also reflected in simulations performed in PSPICE software. The best way to spot the issue was to conduct transient characteristic as it presents the signal in the same form as it can be observed on the oscilloscope's scans presented above. Moreover, numerous simulations performing AC sweep were done, however it is not possible in that case to state clearly that the circuit is operating non-linearly [9, 10]. The signal was simulated for several different amplitudes of the input signal. Strictly speaking, the amplitude was increased linearly, starting from 0.5V up to 12V.

In figure 7, voltage difference between two input terminals of the operational amplifier for the circuit utilizing reference point as a signal ground is presented. Signal frequency is equal to 150Hz as it can serve as the best indicator if the circuit works non-linearly.

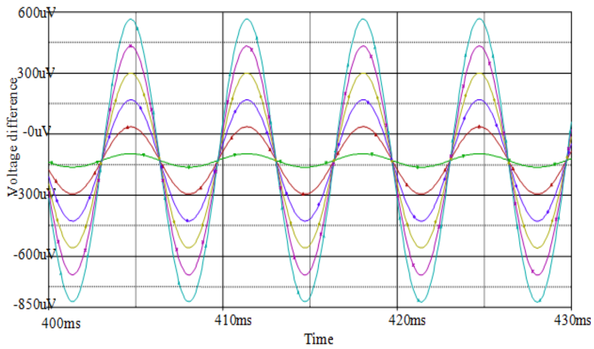


Fig.7. Voltage difference between two input terminals of the operational amplifier for the circuit utilizing reference point as a signal ground. Signal frequency is equal to 150Hz.

In figure 8 the results of similar simulation are presented, however in this case signal frequency is equal to 250Hz.

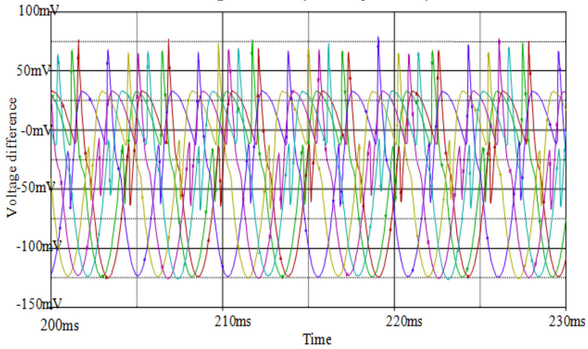


Fig.8. Voltage difference between two input terminals of the operational amplifier for the circuit utilizing reference point as a signal ground. Signal frequency is equal to 250Hz.

As it can be noticed in figure 7 presented above peek-to-peek voltage difference between two input terminals of the op-amp is in the range of 1mV for the signal of frequency 150Hz. The circuit operated linearly up to that frequency, therefore it should be assumed that such a voltage difference is still tolerable and has a negligible influence on the performance of the operational amplifier. The circuit worked non-linearly for 250Hz, the voltage difference is significantly distorted and almost the same for all the amplitudes of an input signal. This is the result of the circuit being in saturation. Moreover, peek-to-peek voltage difference is significantly higher than previously. In that case it is equal to around 200mV, which is two hundred times greater than previously.

In Fig. 9 simulation was done for the input signal of frequency equal to 250Hz and the capacitance at the output of each op-am equal to 470nF, whereas in Fig. 10, input signal's frequency was also equal to 250Hz, but the capacitance was reduced to 100pF. Results are presented for various values of the input voltage from 2V up to 7V.

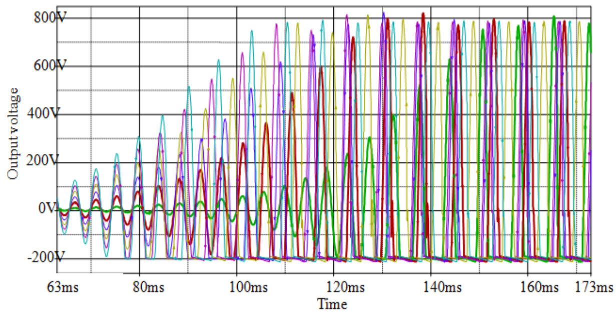


Fig. 9. Transient characteristic of the circuit utilizing reference point as a signal ground. Signal frequency is equal to 250Hz. Capacitors at the outputs of op-amps are equal to 470nF.

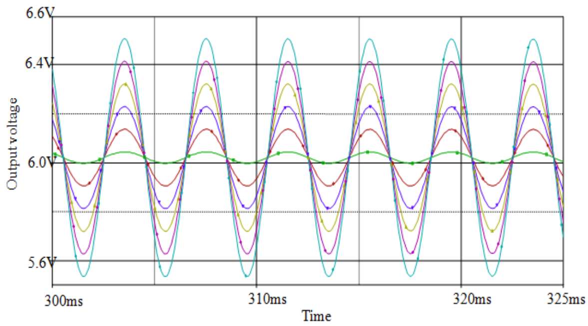


Fig. 10. Transient characteristic of the circuit utilizing reference point as a signal ground. Signal frequency is equal to 250Hz. Capacitors at the outputs of op-amps are equal to 100pF.

As it was mentioned earlier filter operated linearly up to 150Hz, afterwards non-linear operation could be observed and it is reflected in figure 9. However, in figure 10 it might be noticed that reduction of the capacitance helped significantly and the signal is no longer non-linear. On the other hand capacitance was reduced almost five thousand times and the simulations in PSPICE software have shown that the circuit starts to operate non-linearly already for the input signal of frequency equal to 450Hz. Therefore, further reduction of capacitance does not improve the operation of the circuit for considerably higher frequencies and it would led to possible return of the distortions and at the output of the filter and possible excitations.

## Conclusion

In order to recognize the floating ground problem earlier in the future, closer look needs to be taken to the ground loops in the circuit since as it was mentioned they can be a source of significant noise in the floating system. The ground loop can be problematic because stray electromagnetic fields can induce current in the loop and cause a potential difference between two reference nodes [12]. It should be considered if there are any ground loops in the circuit, how significant impact they can have on the operation of the circuit and if there is any way to limit their negative influence on the circuit performance. Especially when the circuit is utilizing operational amplifiers as it was in the case of multiple feedback band-pass filter, even the smallest variation at the non-inverting terminal, which is connected to ground can lead to severe disruption of the circuit operation. As the simulations have shown the circuit would operate linear in the case when earth ground is established in a system. To sum up, causes of the interferences in active filter circuit and reasons behind them were spotted, this provide deeper understanding of the problem and will allow to avoid these issues in the future.

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