Implementation of A Butterworth Bandpass Filter for Heart Sound Detection

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Abstract – Butterworth bandpass filter is a well-known circuit, connecting a Butterworth high pass filter and low pass filter together in a series is the simplest method to create a band pass filter. However, during designing and implementing a filter circuit, the component value tolerance results in the real circuit might be poorly matched the original design. This paper designs and implements a Butterworth band pass filter for a stethoscope to filter noise from heart sounds. An implementation approach for compensating a designed Butterworth band pass filter is proposed to locate the resistor ratio factors for bandpass filters. Three proposed design stages include theoretical design, simulation, and implementation and regulation *work. Experimental results show that the obtained resistor ratio factors are 1.27 for the high pass filter and 1.04 for the low pass filter. The proposed method can also be used to design Butterworth band pass filters for other applications.*

Keywords - stethoscope, heart sound, bandpass filter, Butterworth filter

I. INTRODUCTION

Heart sounds consist of four distinct waves (S_1 to S_4) that repeat in each cardiac cycle with a frequency range of 20Hz to 115Hz. Symptoms of cardiac diseases, such as heart murmurs; occur in a frequency range of 140Hz to 600Hz. Therefore, the frequency range required to diagnosing heart disease is approximately 20Hz to 600Hz [1].

A standard acoustic stethoscope normally has bell mode and diaphragm mode for detecting heart sounds and lung sounds. In most cases, low frequency sounds (ranging from 37.5Hz and 112.5Hz) are amplified by the bell mode, but attenuated by diaphragm mode. Both the bell mode and the diaphragm mode attenuate high frequency sounds (ranging between 125Hz and 1000Hz). The higher the sound frequency is, the more the stethoscope attenuates the sound [2]. A standard acoustic stethoscope consists of a chest piece, a Y-shaped piece of soft tubing, and earpieces [3]. This kind of mechanical structure is highly sensitive to ambient interference, which can negatively affect the listener's ability to judge the patient's condition, however, this noise can be reduce by filters.

Two different band pass filters are required to emulate a standard acoustic stethoscope. One filter has a frequency range of 100 Hz to 500 Hz (diaphragm mode), while the other has a frequency range of 20 Hz to 200 Hz (bell mode). Because the Butterworth type filter has a flat frequency response, connecting a high pass filter to a low pass filter in series creates a band pass filter [4]. The advantages of flat frequency response and wideband characteristics are helpful in filtering heart sound signals.

However, designing and verifying electronic filter circuits is usually time consuming and, in implementation, component value tolerance results in the actual filter circuit often poorly matching the design. This paper proposes a simple filter circuit design method that uses a Butterworth band pass filter to filter out heart noises. The filter circuit can be easily and quickly implemented following three proposed design stages: theoretical design, simulation, and implementation work with resistor ratio factors. The results of experimental measurements of heart sounds indicate that this filter is able to detect heart sounds associated with potential heart disease.

II. CIRCUIT DESIGN

Butterworth type filters have a maximally flat gain response in the pass band, especially at low frequencies [5]. The low frequency ranges of heart sounds and their wide frequency band characteristics make the Butterworth type filter well suited to this type of application. The simplest design of a band pass filter is to connect a high pass filter and a low pass filter in a series [6].

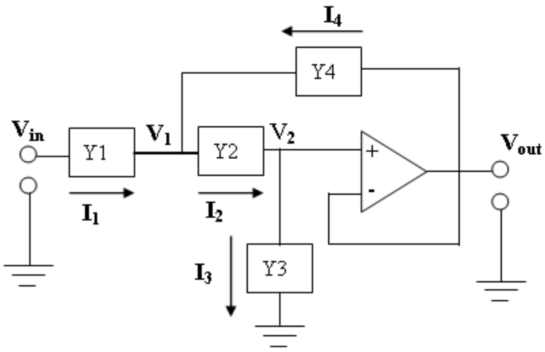


Fig.1 The architecture of a second order filter.

There are four current branches (I_1 to I_4), four conductance components (Y_1 to Y_4) and an operation amplifier (op-amp) with unity gain, as shown in Fig.1. The transfer function of the second order filter is

$$A=V_{out}/V_{in}=(Y_1Y_2)/(Y_1Y_2+Y_1Y_3+Y_2Y_3+Y_3Y_4) \quad (1)$$

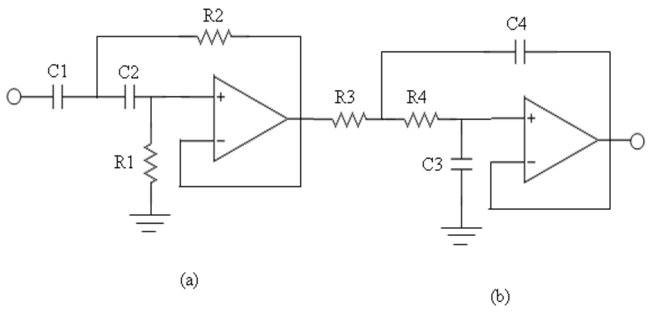


Fig. 2 A typical Fourth order Butterworth band pass filter

Substitute capacitor C_1 and C_2 for Y_1 and Y_2, and resistor R_1 and R_2 for Y_3 and Y_4. In this case, the architecture becomes a second order voltage control voltage source (VCVS) high pass filter (HPF) with unity gain, as shown in Fig. 2a. The transfer function of HPF is [7]

$$A_H(s)=\frac{V_{out}}{V_{in}}(s)=\frac{1}{1+(\frac{1}{R_1C_1}+\frac{1}{R_1C_2})\frac{1}{s}+\frac{1}{R_1R_2C_1C_2}\frac{1}{s^2}} \quad (2)$$

The high pass filter cutoff frequency (f_{H-3dB}) is

$$f_{H-3dB}=\frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} \quad (3)$$

Similarly, substitute resistor R_3 and R_4 for Y_1 and Y_2, and capacitor C_3 and C_4 for Y_3 and Y_4. In this case, the architecture becomes a second order voltage control voltage source (VCVS) low pass filter (LPF) with unity gain, as shown in Fig. 2b. The transfer function of LPF is [7]

$$A_L(s)=\frac{V_{out}}{V_{in}}(s)=\frac{1}{1+[C_3(R_3+R_4)]s+(C_3C_4R_3R_4)s^2} \quad (4)$$

The low pass filter cutoff frequency (f_{L-3dB}) is

$$f_{L-3dB}=\frac{1}{2\pi\sqrt{R_3R_4C_3C_4}} \quad (5)$$

The transfer function of a general second order HPF is

$$A(s)=\frac{A_H}{1+a_1\frac{1}{s}+b_1\frac{1}{s^2}} \quad (6)$$

Where A_H is the pass band gain at dc, while a_1 and b_1 are the filter coefficients.

The coefficients a_1 and b_1 of the Butterworth type HPF are $A_H=1$, $a_1=1.4142$, and $b_1=1$. A coefficient comparison of the transfer function of HPF (2) and (6) yields [8]

$$A_H(s)=\frac{V_{out}}{V_{in}}(s)=\frac{1}{1+1.4142\frac{1}{s}+\frac{1}{s^2}} \quad (7)$$

Equations (2) and (7) show that a_1 and b_1 are

$$a_1=\frac{1}{R_1C_1}+\frac{1}{R_1C_2}=1.4142$$

$$b_1=\frac{1}{R_1R_2C_1C_2}=1 \quad (8)$$

To simplify the above equation, suppose that $C_1= C_2$. Thus, the relation between parameter R_1 and R_2 is

$$R_1=2R_2 \quad (9)$$

Therefore, in designing a Butterworth high pass filter with a cutoff frequency of f_H, the resister R_2 can be quickly determined by just giving the value of C_2 as:

$$R_2=\frac{1}{2\pi f_H C_2\sqrt{2}} \quad (10)$$

The transfer function of a general second order LPF is

$$A(s)=\frac{A_L}{1+a_1s+b_1s^2} \quad (11)$$

Where A_L is the pass band gain at dc, while a_1 and b_1 are the filter coefficients.

The coefficients a_1 and b_1 of the Butterworth type LPF are $A_L=1$, $a_1=1.4142$, and $b_1=1$. A coefficient comparison of the transfer function of LPF (4) and (11) yields [8]

$$A_L(s)=\frac{V_{out}}{V_{in}}(s)=\frac{1}{1+1.4142s+s^2} \quad (12)$$

Equations (4) and (12) reveal that a_1 and b_1 are

$$a_1=C_3(R_3+R_4)=1.4142$$

$$b_1=C_3C_4R_3R_4=1 \quad (13)$$

To simplify the above equation, suppose $R_3=R_4$. Thus, the relation between parameter C_4 and C_3 is

$$C_4=2C_3 \quad (14)$$

Therefore, in designing a Butterworth low pass filter with a cutoff frequency of f_L, the resister R_4 can be quickly determined by just giving a value of C_3 as:

$$R_4=\frac{1}{2\pi f_L C_3\sqrt{2}} \quad (15)$$

This paper cascades Butterworth type HPF and LPF into a band pass filter. As shown in Fig. 2, after simplifying the filter architecture, only four components remain to be determined: $C_1=C_2=C_H$, $R_1=2R_2$ for HPF, and $R_3=R_4$, $C_4=2C_3$ for LPF. Therefore, according to (10), the values of resistors R_1 and R_2 can be easily calculated by giving a proper C_2 ($C_1=C_2$) for a HPF with cutoff frequency of $f_{H(-3dB)}$. According to (15), the values of resistors R_3 and R_4 can be easily calculated by giving a proper C_3 ($C_4=2C_3$) for a LPF with a cutoff frequency of $f_{L(-3dB)}$.

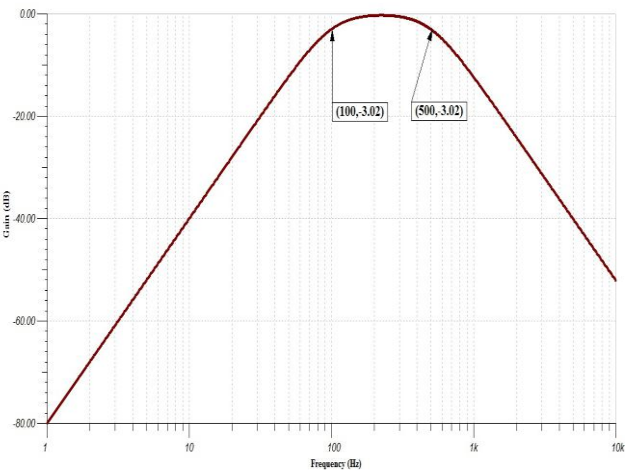
III. RESULTS AND DISCUSSION

This paper uses three proposed stages to implement a band pass filter for heart sounds measurement application on a stethoscope.

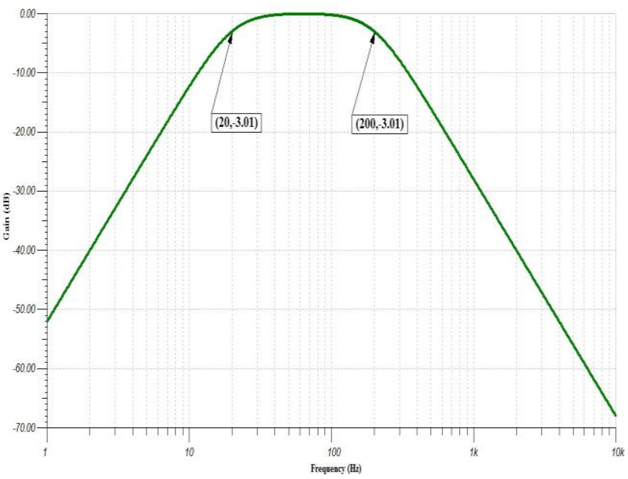
First, the designed values of R and C were calculated using equations based on the simplified filter architecture described in the previous section. For a HPF design, let $C_1=C_2=0.22\mu F$. According to (10), $R_1=10.23$ kΩ and $R_2=5.12$ kΩ by giving $f_{H(-3dB)}=100Hz$, or $R_1=51.15$ kΩ and $R_2=25.58k\Omega$ by giving $f_{H(-3dB)}=20Hz$. For a LPF design, let $C_3=5.6nF$; then $C_4=11.2nF$. According to (15), $R_3=R_4=R_L=40.19$ kΩ for $f_{L(-3dB)}$ = 500Hz, or

R_3=R_4=R_L=100.48 kΩ for $f_{L(-3dB)}$=200Hz.

To identify the above-mentioned designed values for R and C, a simulation tool called TINA-TI [9], which supports Butterworth type filters, is used to verify the feasibility of the theoretical calculation values. Fig.3 shows the amplitude attenuation results of simulations produced in simulations with the above-mentioned designed values of R and C: -3.02dB at 100 Hz and -3.02 dB at 500 Hz or -3.01 dB at 20 Hz and -3.01dB at 200 Hz. Those values obviously conform to the theoretical calculations.



(a)

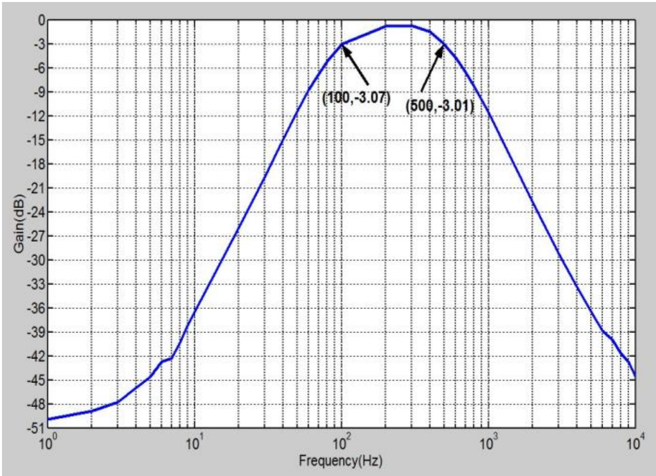


(b)

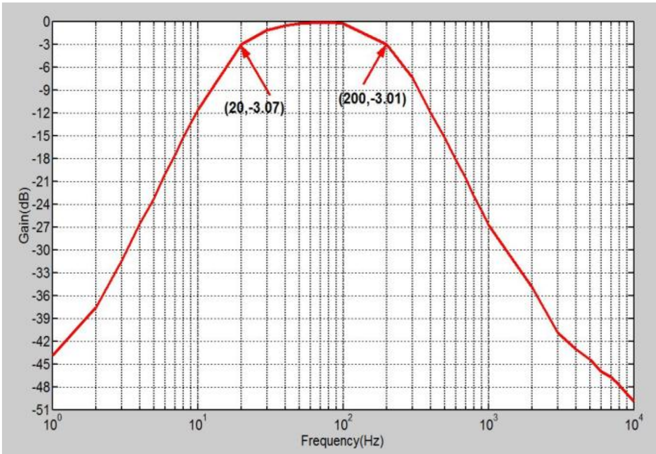
Fig. 3 Simulated amplitude attenuation of a Butterworth band pass filter (a) -3.02dB at 100 Hz and -3.02 dB at 500 Hz (b) -3.01 dB at 20 Hz and -3.01dB at 200 Hz

Finally, a real band pass filter circuit is implemented with the above-mentioned R and C values. Due to mismatch between real resistor values and theoretical calculation values, take resistor values 10.2 kΩ and 5.11 kΩ instead of theoretical calculation values 10.23kΩ 5.12 kΩ, and capacitor value 0.22μF for 100Hz of HPF. The cutoff frequency response value of 100Hz HPF is -5.10dB. As this value is below -3.0dB, the resistor values with real resistors is increased by experiment. The resistors 13.0 kΩ and 6.49 kΩ produce a -3.07dB response value for 100Hz HPF. Additionally, take resistor value 40.2 kΩ and capacitor values 5.6nF and 11.2nF for 500Hz of LPF. The cutoff frequency response value of 500Hz LPF is -2.79dB. As this value is greater than -3.0dB, the resistor value with real resistors is increased by experiment. The resistors 41.2kΩ make -3.01dB response value for 500Hz LPF.

Similarly, take resistor values 51.1 kΩ and 25.5 kΩ instead of theoretical calculation values 51.15kΩ and 25.58kΩ, and capacitor value 0.22μF for 20Hz of HPF. The cutoff frequency response value of 20Hz HPF is -5.16dB. As this value below -3.0dB, the resistor values with real resistors increase by experiment. The resistors 64.9 kΩ and 32.4 kΩ produce a -3.07dB response value for 20Hz HPF. Additionally, take resistor value 100 kΩ and capacitor values 5.6nF and 11.2nF for 200Hz of LPF. The cutoff frequency response value of 200Hz LPF is -2.85dB. As this value is greater than -3.0dB, the resistor value with real resistors is increased by experiment. The resistors 105kΩ produce a -3.01dB response value for 200Hz LPF.



(a)



(b)

Fig.4 Physical responses of an implemented Butterworth band pass filter circuit (a) -3.07dB at 100 Hz and -3.01 dB at 500 Hz (b) -3.07 dB at 20 Hz and -3.01dB at 200 Hz

Fig.4 shows the physical frequency responses of two real filter circuits for use in the 100 Hz to 500 Hz and 20 Hz to 200 Hz frequency ranges, which the amplitude attenuations for the cutoff frequencies of 100 Hz and 500Hz are –3.07dB and –3.01dB, respectively, and the amplitude attenuations for the cutoff frequencies of 20 Hz and 200Hz are –3.07dB and –3.01 dB, respectively. Experimental results indicate that this physical filter meets the design requirements of both band pass filters.

Tables I and II show the experimental results of fine-tuning the resistor values with stationary capacitor values.

In Table I, resistor values 64.9 kΩ and 51.1 kΩ have a ratio factor of 1.27, and resistor values 32.4 kΩ and 25.5 kΩ also have ratio factor of 1.27. Resistor values 105 kΩ and 100 kΩ have a ratio factor of 1.05. In Table II, resistor values 13.0 kΩ and 10.2 kΩ have a ratio factor of 1.27, and resistor values 6.49 kΩ and 5.11 kΩ also have a ratio factor of 1.27. Resistor values 41.2 kΩ and 40.2 kΩ have ratio factor 1.03. To show the ratio factor results, the theoretical value multiplies 1.27 to obtain the real HPF resistor value, and the theoretical value multiplies 1.05 to obtain the real LPF resistor value. These results save time in choosing components for implementing the filter circuit, and improve circuit accuracy.

Table III shows parameter comparisons of a fourth order Butterworth band pass filter for signals in the frequency range 100 Hz to 500 Hz (diaphragm mode) during the three stages. Table IV shows parameter comparisons of a fourth order Butterworth band pass filter for signals in the frequency range of 20 Hz to 200 Hz (bell mode) during the three stages.

Furthermore, the performance of the constructed filter was examined with a short stethoscope signal from a human heart sound. Fig. 5 shows the profiles of both the original signal and filtered signal with a Lecroy LT344 oscilloscope. The upper channel illustrates the original heart signal, which only passes through an amplifier circuit without a Butterworth band pass filter. The noise is so significant that signal profile is quite different from a typical heart sound. The lower channel illustrates the filtered heart signal, which passes through an amplifier circuit with the Butterworth band pass described above.

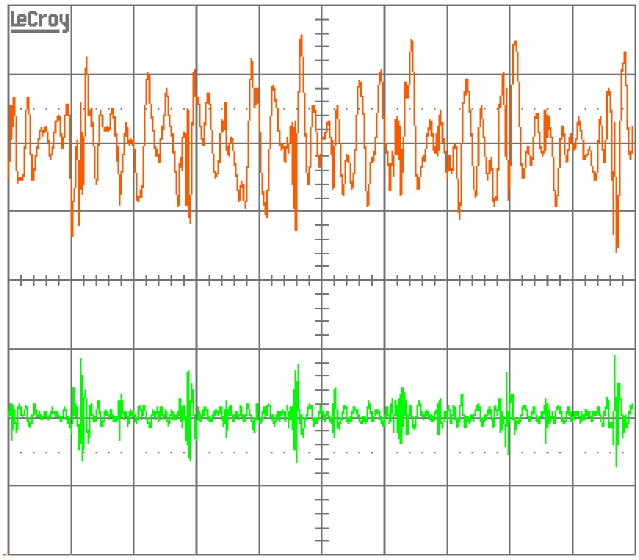


Fig. 5 Comparison of non-filtered (upper channel) and filtered (lower channel) heart sound with an oscilloscope

IV. CONCLUSIONS

This paper proposes a compensation approach for implementing a Butterworth band pass filter to filter noise of heart sounds. A band pass filter circuit can be quickly and easily implemented following three proposed stages: theoretical design, simulation, and implementation and regulation with a resistor ratio factor. A Butterworth band pass filter is built for a stethoscope to filter the noise of heart sounds. Experimental results show an adjusted ratio factor for the theoretical calculation value is 1.27 for HPF, and 1.04 for LPF to achieve a better filtering performance. The proposed filter is helpful for an electronic stethoscope to detect heart sounds associated with potential heart diseases.

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TABLE I

Real resistor value on fine-tuning step for 100Hz HPF and 500Hz LPF filters

For HPF		
$C_1=C_2=0.22\mu$ F		
$R_1=2R_2$	Resistor value	-3dB @ 100Hz
$R_1(R_2)$	10.2k (5.11k)	-5.10
$R_1(R_2)$	12.1k (6.04k)	-3.84
$R_1(R_2)$	12.4k (6.2k)	-3.41
$R_1(R_2)$	12.7k (6.34k)	-3.30
$R_1(R_2)$	13k (6.49k)	-3.07
The ratio of the final resistor to the initial resistor is 1.27 (=13k/10.2k).		
For LPF		
C_3=5.6nF, C_4=11.2nF		
$R_3=R_4$	Resistor value	-3dB @ 500Hz
	40.2k	-2.79
	41.2k	-3.01
The ratio of the final resistor to the initial resistor is 1.03(=41.2k/40.2k).		

TABLE II

Real resistor value on fine-tuning step for 20Hz HPF and 200Hz LPF filters

For HPF		
$C_1=C_2=0.22\mu$ F		
$R_1=2R_2$	Resistor value	-3dB @ 20Hz
$R_1(R_2)$	51.1k (25.5k)	-5.16
$R_1(R_2)$	53.6k (27k)	-4.82
$R_1(R_2)$	60.4k (30k)	-3.53
$R_1(R_2)$	63.4k (31.6k)	-3.19
$R_1(R_2)$	64.9k (32.4k)	-3.07
The ratio of the final resistor to the initial resistor is 1.27 (=64.9k/51.1k).		
For LPF		
C_3=5.6nF, C_4=11.2nF		
$R_3=R_4$	Resistor value	-3dB @ 200Hz
	100k	-2.85
	105k	-3.01
The ratio of the final resistor to the initial resistor is 1.05 (=105k/100k).		

TABLE III

Parameter Comparisons of a Fourth order Butterworth band pass filter for the frequency range of 100Hz to 500Hz signal during three stages

Stage / Frequency	Theoretical design	Simulation (Theoretical value)	Implementation (real work)
100 Hz (high pass)	R_1=10.23 kΩ R_2=5.12kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.0 dB	R_1=10.23 kΩ R_2=5.12kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.02 dB	R_1=13 kΩ R_2=6.49kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.07 dB
500 Hz (low pass)	R_3=40.19 kΩ R_4=40.19kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.0 dB	R_3=40.19 kΩ R_4=40.19kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.02 dB	R_3=41.2 kΩ R_4=41.2kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.01 dB

TABLE IV

Parameter Comparisons of a Fourth order Butterworth band pass filter for the frequency range of 20Hz to 200Hz signal during three stages

Stage / Frequency	Theoretical design	Simulation (Theoretical value)	Implementation (real work)
20 Hz (high pass)	R_1=51.15kΩ R_2=25.58kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.0 dB	R_1=51.15kΩ R_2=25.58kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.01 dB	R_1=64.9kΩ R_2=32.4kΩ $C_1=0.22\mu$ F $C_2=0.22\mu$ F $A_{H=}$-3.07 dB
200 Hz (low pass)	R_3=100.48kΩ R_4=100.48kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.0 dB	R_3=100.48kΩ R_4=100.48kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.01 dB	R_3=105kΩ R_4=105kΩ C_3=5.6nF C_4=11.2nF $A_{L=}$-3.01 dB