Universidade do Minho
Escola de Engenharia

The-RLC-circuit-as-a-frequency-filter-series-and-parallel-

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Summary

This work aimed to analyze the behavior of RLC circuits, in resonance, both in series and in parallel. By assembling bandpass filters and due to the frequency response, the resonance frequency, bandwidth and quality of each circuit were determined. With these results, the equations that allow obtaining the theoretical values were confirmed. By varying the resistance and capacitor, it was also confirmed that in the series circuit, the bandwidth is directly proportional to the resistance, but does not vary with the capacitor. On the other hand, in the parallel circuit, the bandwidth is inversely proportional to the resistance and the capacitor.

1. Introduction

Circuits that include coils, capacitors and resistors are normally used as frequency filters and can perform different functions. For example, they operate as band-pass filters (LCR), allowing only a portion of the frequency spectrum to pass through. They also act as band-reject filters (RLC), which complement the function of band-pass filters, or as high-pass filters (RCL) or low-pass filters (RLC), where higher or lower frequencies are eliminated, depending on the circuit configuration.

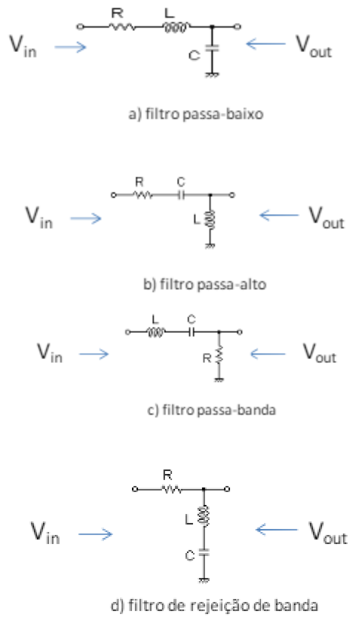

Figure 1 – Applications of RLC configurations as frequency filters.

In this work, the focus was on the circuit that operates as a band-pass filter. In the resonance situation, the 180° phase difference between the inductive (ZL) and capacitive (Zc) reactances causes the total reactance to cancel out, that is:

$$ZL + Zc = 0 \qquad (1)$$

Resulting in a resonance frequency given by (see appendix 1), for which the circuit is purely resistive, that is, the output is in phase with the input:

$$\omega_o = \frac{1}{\sqrt{LC}} \qquad (2)$$

In the RLC circuit represented in figure 1d) we have, in the vicinity of the resonance frequency, a low output impedance (practically zero), resulting in small amplitude signals. In contrast, in the RLC circuit in figure 1c) we have, in the vicinity of the resonance frequency, a high output impedance, which leads to signals of large amplitude.

Figure 2 graphically represents the gain (|Vout/Vin|) as a function of frequency, demonstrating the response of these circuits, where | $Vout/\ Vin$ | is the resonance frequency and β is the bandwidth.

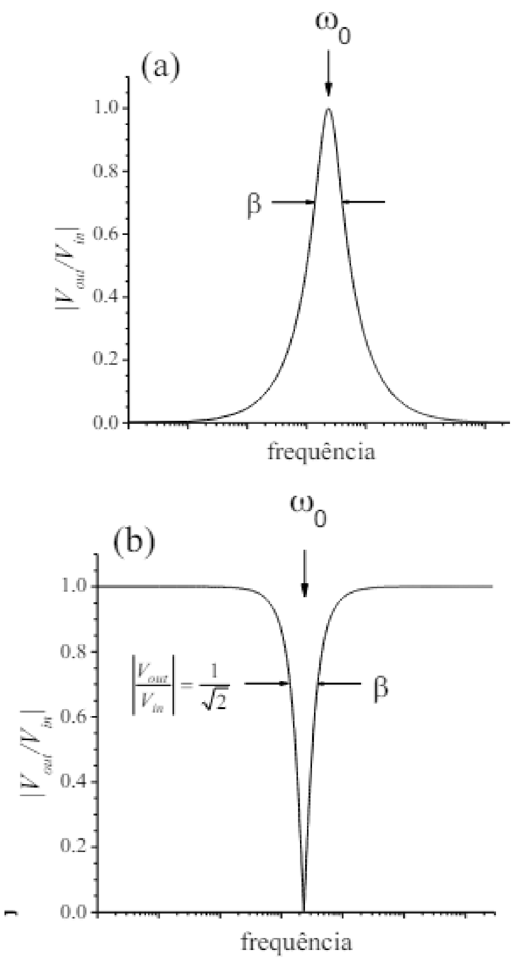

Figure 2 – Response of a bandpass filter (a) and a bandreject filter (b). Frequency in Hz.

When the capacitor and the coil are placed in parallel and this set in series with a resistor, illustrated in the following figure:

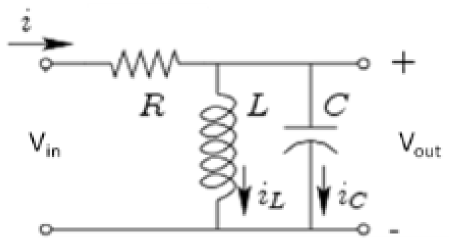

Figure 3 – Parallel RLC circuit.

In the resonance situation, the currents iC and iL (from the capacitor and the coil, respectively) are 180° out of phase, canceling each other out. Thus, in a parallel RLC circuit, current practically does not flow, indicating a very high resistance, which, in the limit, is an open circuit.

In these circuits and for frequencies in the vicinity of the resonance frequency, the output signals will be of large amplitude. In other words, the output measured at the terminals of the capacitor and coil assembly in parallel will function as a band-pass filter, with a frequency response similar to Figure 2(a).

However, it remains to define the parameter β, which represents the bandwidth, that is, the frequency range where the amplitude of the output signals is greater (in the case of the band-pass filter) or less (in the case of the band-reject filter) than the amplitude of the input signal divided by √2. That is, for the two frequencies $\omega 1$ and $\omega 2$ where the gain $|Vout/Vin|$ = 1/√2, resulting in a bandwidth equal to:

$$\beta = \omega 2 - \omega 1 \qquad (3)$$

With this, we can conclude that if we want a circuit with a wide frequency range, we have to guarantee a small bandwidth. Therefore, the choice of frequencies to select depends on both the resonance frequency and the bandwidth. This characteristic is expressed by the quality factor Q, defined by the expression (common to all analyzed circuits):

$$Q = \frac{\omega_0}{\beta} \qquad (4)$$

For the particular case of the series RLC circuit we have:

$$\beta = \omega_2 - \omega_1 = \frac{R}{L} \qquad (5)$$

$$Q = \frac{\omega_0}{\beta} = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad (6)$$

And for the particular case of the parallel RLC circuit we have:

$$\beta = \omega_2 - \omega_1 = \frac{1}{RC} \qquad (7)$$

$$Q = \frac{\omega_0}{\beta} = \omega_0 RC = R\sqrt{\frac{C}{L}} \qquad (8)$$

2. Material used and procedure

Material used:

- Resistance (1 KΩ; 3,7KΩ; 3,3KΩ);
- Capacitor (15 nF; 25 nF; 14 nF; 47nF);
- Inductor (106 mH);
- AC source;
- Multimeters;
- Oscilloscope;
- Connection wires;

This experience can be divided into two distinct parts. In the first part, an analysis of a series RLC circuit was carried out, while in the second part, we focused on the study of a parallel RLC circuit.

In the first part, a series RLC circuit was assembled as shown in figure 4.

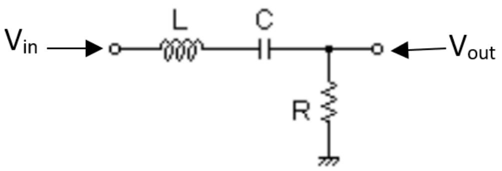

Figure 4: Series RLC circuit (bandpass filter).

As input signal, Vin, a sinusoid with 10 Vpp was used. To apply this value to the input, an alternating voltage (AC) source was used. This value was adjusted using the automatic measurement options of the oscilloscope, which was connected to the circuit via test leads.

To experimentally determine the resonance frequency, a 15 nF capacitor, a 106 mH inductor and a 1 kΩ resistor were used. These values were kept constant during all measurements. The input signal frequency was varied between 1 kHz and 13 kHz, increasing in 0.5 kHz steps. These frequency values were adjusted using the oscilloscope's automatic frequency measurement. For each frequency value, measurements of the amplitude of the output signal, Vout, were taken using the automatic measurement options of the oscilloscope, which was connected to the circuit by means of test leads.

Subsequently, to evaluate the impact of the resistance variation on the filter bandwidth, a resistance with a different value, 3.7 kΩ, was used. The capacitor and coil used were the same as in the previous assembly. Then, the procedure of measuring the values of the amplitude of the output signal, Vout, was repeated while the frequency of the input signal was varied, as performed previously.

Then, in order to verify the effect of the variation of the L/C ratio on the bandwidth of the band-pass filter, capacitors with different capacitances were used. During all measurements, the resistance was kept constant at 1 kΩ and the coil at 106 mH. Then, the procedure of measuring the amplitude values of the output signal, Vout, was repeated while varying the frequency of the input signal.

In the second part, an RLC circuit was assembled in parallel as shown in figure 5.

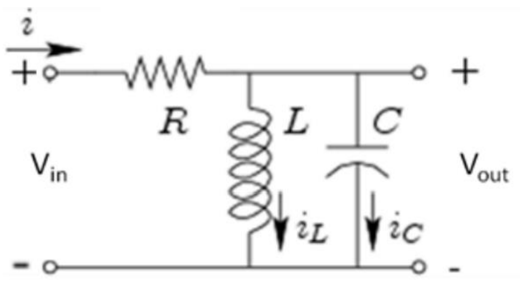

Figure 5: RLC circuit in parallel.

As input signal, Vin, a sinusoid with 10 Vpp was used. To introduce this signal at the input, we use an alternating voltage (AC) source. The adjustment of this parameter was done in the same way as in the previous part, using the oscilloscope's measurement functionalities.

To experimentally determine the resonance frequency, a 15 nF capacitor, a 119 mH inductor and a 1 kΩ resistor were used. These values were kept constant during all measurements. Then, proceed in the same way as before, measuring the output voltage while varying the input frequency.

To evaluate the impact of resistance variation on the filter bandwidth, a resistance with a different value, 3.3 kΩ, was used. The capacitor and inductor used were the same. Then, the procedure of measuring the values of the amplitude of the output signal, Vout, was repeated.

To study the effect of varying the L/C ratio on the bandwidth of the band-pass filter, capacitors with different capacitances were used. The resistance was kept constant at 1 kΩ and the inductor at 116 mH. Then, the procedure of measuring the values of the amplitude of the output signal, Vout, was repeated.

One thing you should be careful about when performing this experiment is to always keep the input signal voltage constant. To ensure this, it is recommended to view both the input and output signal shapes on the oscilloscope. If the input signal voltage decreases, this variation can be detected and adjusted back to its initial value.

3. Presentation of results and calculations

3.1. Series RLC circuit

Table 1 shows the values of the components used in assembling the circuit in Figure 4, including the capacitance of the capacitor C, the self-induction coefficient of the coil L and the resistance R. The coil resistance value and the total resistance of the circuit are also displayed. These values were used to determine the resonant frequency of this circuit.

Table 1: Values of the capacitance of the capacitor C, the self-induction coefficient of the inductorl L, the resistance R, the resistance of the inductor and the total resistance of the circuit. The uncertainty of R and R_L were estimated based on the specifications provided by the multimeter manufacturer, while that of R_total was obtained using equation (A. 19).

L (H)	0,106
C (F)	15×10^{-9}
$R \pm \sigma_R (\Omega)$	1000 ± 10
$R_L \pm \sigma_{R_L} (\Omega)$	65 ± 1
$R_{total} \pm \sigma_{R_{total}} (\Omega)$	1065 ± 10

Figure 6 shows the graph of gain (Vout/Vin) as a function of the input signal frequency for the values in Table 25 of the appendix. This table contains the gain values, which is the amplitude of the output signal over the amplitude of the input signal, for each of the frequencies applied to the circuit input. The input signal amplitude was kept constant at 5V for the circuit that was assembled with the components specified in Table 1.

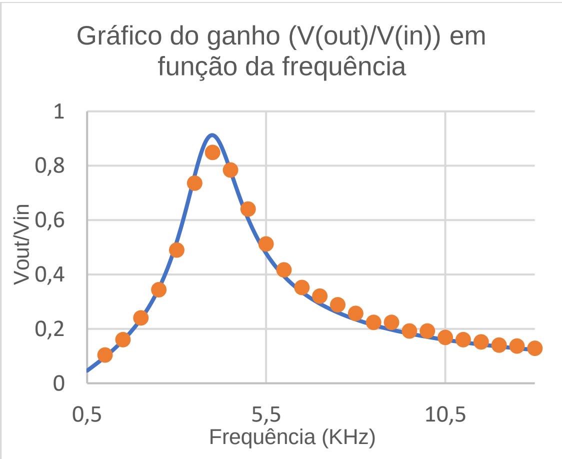

Figure 6: Representation of the experimental points of the gain as a function of frequency and

the Gaussian function that best fits the experimental points.

Table 2 presents the values of the experimental resonance frequency (frequency at which the gain is maximum) and the theoretical values obtained through equation (2), together with the respective relative error.

Table 2: Values of the resonance frequency of the experimental and theoretical band-pass filter. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum.

	Experimental	σ	Theoretical	Error (%)
f_0 (Hz)	4000	5	3991,37	0,22
ω_0 (rad/s)	25132,7	31,4	25078,5	0,22

Table 3 presents the cutoff frequency values, i.e. the angular frequency values for which the gain is $1/\sqrt{2}$.

Table 3: Cutoff frequency values. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is $1/\sqrt{2}$.

f1 (Hz)	3300$\pm$5	ω1 (rad/s)	20735$\pm$31
f2 (Hz)	4750$\pm$5	ω2 (rad/s)	29845$\pm$31

Table 4 presents the experimental and theoretical bandwidth values, β, calculated respectively by equations (3) and (5), and in addition to the experimental quality factor, Q, obtained by equation (4), and the theoretical one obtained through equation (6), for this band-pass filter configuration. The relative error values are also calculated for both cases.

Table 4: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix.

	Experimental	σ	Theoretical	Error (%)
β (rad/s)	9111	45	10047	9,32
Q	2,76	0,02	2,50	10,52

To evaluate how resistance influences the filter behavior, a different resistance from the previous one was used, in order to allow visualization of the effect of its variation. Table 5 shows the values of the components used in assembling the circuit in Figure 4.

Table 5: Values of the component characteristics in the assembly of this circuit. The uncertainty of R and R_L were estimated based on the specifications provided by the multimeter manufacturer, while that of R_total was obtained using equation (A. 19).

L (H)	0,106
C (F)	15×10^{-9}
R $\pm \sigma_R (\Omega)$	3700$\pm$35
$R_L \pm \sigma_{R_L} (\Omega)$	65$\pm$1
$R_{total} \pm \sigma_{R_{total}}$ (Ω)	3765$\pm$35

Figure 7 shows a graph that represents how the gain (the ratio of the output voltage to the input voltage) varies with the frequency of the input signal. These were created with the values listed in Table 26, present in the appendix, which indicates the gain for different frequencies applied to the circuit. The input signal voltage was kept constant at 5V for the circuit assembled with the components described in Table 5.

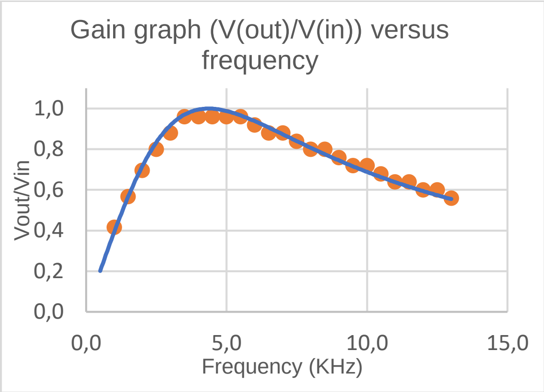

Figure 7: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points.

Table 6 shows the values of the experimental and theoretical resonance frequency (frequency at which the gain is maximum) and the theoretical values obtained through equation (2), together with the corresponding relative error.

Table 6: Values of the resonance frequency of the experimental and theoretical band-pass filter. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum.

	Experimental	σ	Theoretical	Error (%)
f_0 (Hz)	4000	5	3991,37	0,22
ω_0 (rad/s)	25132,7	31,4	25078,5	0,22

Table 7 shows the cutoff frequency values, which are the angular frequency values at which the gain is equal to 1/√2.

Table 7: Cutoff frequency values. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is $1/\sqrt{2}$.

f1 (Hz)	3000 ± 5	ω1 (rad/s)	12566 ± 31
f2 (Hz)	9500 ± 5	ω2 (rad/s)	59690 ± 31

Table 8 shows the experimental and theoretical bandwidth values, β, calculated respectively by equation (3) and (5), as mentioned in the introduction, together with the experimental quality factor, denoted as Q, obtained by equation (4), and the theoretical one obtained through equation (6), for the specific band-pass filter configuration. The relative error values are also calculated for both cases.

Table 8: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix.

	Experimental	σ	Theoretical	Error (%)
β (rad/s)	47124	45	35519	32,67
Q	0,53	0,01	0,71	24,46

To investigate how varying the L/C ratio affects the bandwidth of the band-pass filter, capacitors with different capacitances were used. This allowed us to observe the effect of this variation. For this, the experimental part was carried out twice: once with a 25nF capacitor, C1, and once with two capacitors in series, one of 14nF and the other of 14.5nF, totaling approximately 7nF, C2. The values of the components used in assembling the circuit shown in Figure 4 are detailed in Tables 9.

Table 9: Values of the component characteristics in the assembly of this circuit. The uncertainty of R and R_L were estimated based on the specifications provided by the multimeter manufacturer, while that of R_total was obtained using equation (A.19) Capacitor C2 was obtained by placing capacitor C2' in series with C2".

L (H)	0,106
C1 (F)	25×10^{-9}
C2’ (F)	14×10^{-9}
C2’’ (F)	$14,5 \times 10^{-9}$
C2 (F)	$7,2 \times 10^{-9}$
$R \pm \sigma_R (\Omega)$	1000 ± 10
$R_L \pm \sigma_{R_L} (\Omega)$	65 ± 1

$R_{total} \pm \sigma_{R_{total}}$ (Ω)	1065±10

Figures 8 and 9 present graphs that demonstrate how the gain of this circuit varies in relation to the frequency of the input signal when using capacitors C1 and C2, respectively. Having been obtained through the values contained in Tables 27 and 28, present in the appendix. During both assemblies of this circuit, the amplitude of the input sinusoid was kept constant at 5V.

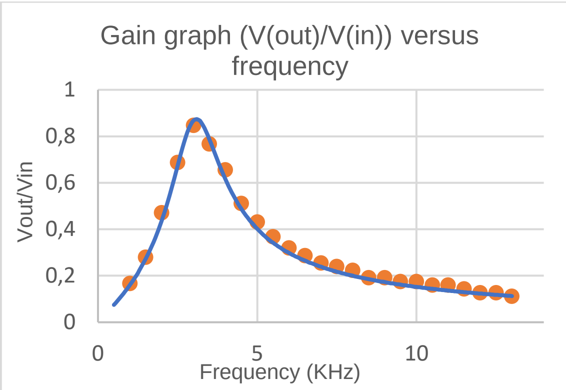

Figure 8: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points, when using the 25nF capacitor C1.

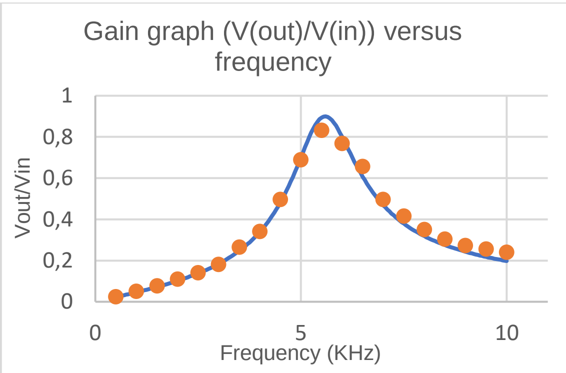

Figure 9: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points, when using the 7nF capacitor C2.

Table 10 presents the values of the resonance frequency (frequency at which the gain is maximum) and the theoretical values obtained through equation (2), accompanied by the corresponding relative error, for the circuit using capacitors C1 and C2.

Table 10: Values of the resonance frequency of the experimental and theoretical band-pass filter. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum.

		Experimental	σ	Theoretical	Error (%)
C1	f_0 (Hz)	5500	5	5469,43	0,56
	ω_0 (rad/s)	34557,5	31,4	34365,4	0,56
C2	f_0 (Hz)	3000	5	3091,7	2,97
	ω_0 (rad/s)	18849,6	31,4	19425,7	2,97

Table 11 presents the cutoff frequency values, which represent the angular frequencies at which the gain is equal to 1/√2.

Table 11: Cutoff frequency values. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is 1/$\sqrt{2}$.

C1	f1 (Hz)	2550±5	ω1 (rad/s)	16022±31
	f2 (Hz)	3900±5	ω2 (rad/s)	24504±31
C2	f1 (Hz)	5250±5	ω1 (rad/s)	32987±31
	f2 (Hz)	6650±5	ω2 (rad/s)	41783±31

Table 12 presents the experimental and theoretical bandwidth values, represented as β, calculated respectively by equations (3) and (5), as mentioned in the introduction. Furthermore, the experimental and theoretical quality factor, denoted as Q, obtained by equation (4) and (6) are provided. The relative error values for both data sets are also calculated for each of the assemblies made with the respective capacitor.

Table 12: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix.

		Experimental	σ	Theoretical	Error (%)
C1	β (rad/s)	8482	45	10047	15,58
	Q	2,22	0,02	1,93	14,94
C2	β (rad/s)	8797	45	8403	4,68
	Q	3,93	0,02	4,09	3,93

3.2. Parallel RLC circuit

Table 13 shows the values of the components used in assembling the circuit in Figure 5, including the capacitance of the capacitor C, the self-induction coefficient of the inductor L and the resistance R. The inductor resistance value and the total resistance of the circuit are also displayed. These values were used to determine the resonant frequency of this circuit.

Table 13: Values of the capacitance of the capacitor C, the self-induction coefficient of the inductor L, the resistance R, the resistance of the inductorl and the total resistance of the circuit. The uncertainty of R and R_L were estimated based on the specifications provided by the multimeter manufacturer, while that of R_total was obtained using equation (A.21)

L (H)	0,119
C (F)	47×10^{-9}
$R \pm \sigma_R(\Omega)$	1000 ± 10
$R_L \pm \sigma_{R_L}(\Omega)$	65 ± 1
$R_{total} \pm \sigma_{R_{total}}(\Omega)$	1002 ± 10

Figure 10 shows the gain graph $\left(\frac{V_{OUT}}{V_{IN}}\right)$ as a function of the frequency of the input signal for the values in Table 29 of the appendix. This table contains the gain values, which is the amplitude of the output signal over the amplitude of the input signal, for each of the frequencies applied to the circuit input. The input signal amplitude was kept constant at 5V.

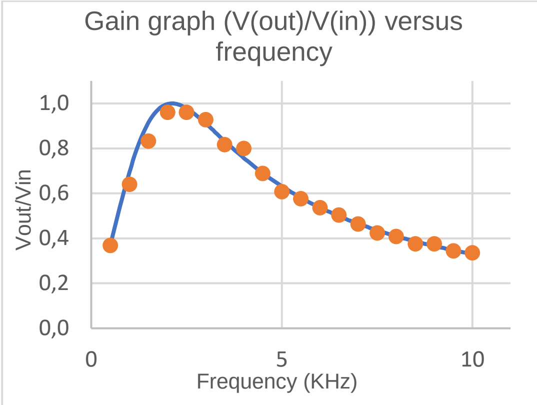

Figure 10: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points.

Table 14 presents the values of the experimental resonance frequency (frequency at which the gain is maximum) and the theoretical values obtained through equation (2), accompanied by the corresponding relative error.

Table 14: Values of the resonance frequency of the experimental and theoretical band-pass filter. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum.

	Experimental	σ	Theoretical	Error (%)
f_0 (Hz)	2200	5	2115	4,02
ω_0 (rad/s)	138233	32	13288	4,02

Table 15 presents the cutoff frequency values, which correspond to the angular frequencies at which the gain is equal to $1/\sqrt{2}$.

Table 15: Cutoff frequency values. The uncertainty of the experimental value was estimated at

5Hz due to the difficulty in identifying the exact frequency where the gain is 1/$\sqrt{2}$.

f1 (Hz)	1100$\pm$5	ω1 (rad/s)	6912$\pm$31
f2 (Hz)	4400$\pm$5	ω2 (rad/s)	27646$\pm$31

Table 16 presents the values of the experimental and theoretical bandwidth, β, calculated respectively by the expressions mentioned in the introduction. Furthermore, the experimental and theoretical quality factor, denoted as Q, obtained by the expression mentioned in the introduction, are provided. The relative error values for the two values are also calculated.

Table 16: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix.

	Experimental	σ	Theoretical	Error (%)
β (rad/s)	20734	45	21013	1,32
Q	0,67	0,01	0,63	5,42

To visualize how the resistance variation affects the filter behavior, a different resistance was used. The values of the components used in assembling the circuit in Figure 5 are presented in Table 17.

Table 17: Values of the component characteristics in the assembly of this circuit. The uncertainty of R and R_L were estimated based on the specifications provided by the multimeter manufacturer, while the R_{total} was obtained by means of equation (A. 21)

L (H)	0,119
C (F)	47×10^{-9}
R $\pm \sigma_R (\Omega)$	3300$\pm$31
$R_L \pm \sigma_{R_L} (\Omega)$	65$\pm$1
$R_{total} \pm \sigma_{R_{total}}$ (Ω)	3302$\pm$31

Figures 11 show graphs that demonstrate how the gain of this circuit varies in relation to the frequency of the input signal. Having been obtained through the values contained in Table 30, present in the appendix. During the assembly of this circuit, the amplitude of the input sinusoid was kept constant at 5V, with only its frequency varying.

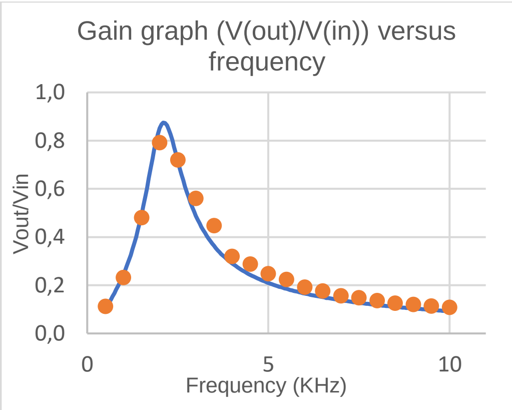

Figure 11: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points.

Table 18 shows the values of the experimental resonance frequency (frequency at which the gain is maximum) and the theoretical values obtained through equation (2), together with the corresponding relative error.

Table 18: Values of the resonance frequency of the experimental and theoretical band-pass filter. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum.

	Experimental	σ	Theoretical	Error (%)
f_0 (Hz)	2200	5	2115	4,02
ω_0 (rad/s)	138233	32	13288	4,02

Table 19 shows the cutoff frequency values, which indicate the angular frequencies at which the gain is equal to 1/√2.

Table 19: Cutoff frequency values. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is 1/$\sqrt{2}$.

f1 (Hz)	1650$\pm$5	ω1 (rad/s)	10367$\pm$31
f2 (Hz)	2700$\pm$5	ω2 (rad/s)	16965$\pm$31

Table 20 presents the values of the experimental and theoretical bandwidth, β. In addition, the experimental and theoretical quality factor, denoted as Q, are provided. The relative errors corresponding to each measurement are also presented.

Table 20: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix..

	Experimental	σ	Theoretical	Error (%)
β (rad/s)	6597	45	6368	3,61
Q	2,10	0,02	2,09	0,40

Table 21 shows the values of the components used in assembling the circuit shown in Figure 5. This circuit was assembled with the purpose of investigating the effect of varying the L/C ratio on the filter behavior, that is, how this affects the bandwidth and resonance frequency. For this purpose, two capacitors in series were used, one of 14nF and the other of 47nF, totaling approximately 10nF (C1).

Table 21: Values of the component characteristics in the assembly of this circuit. The uncertainty of R e R_L were estimated based on the specifications provided by the multimeter manufacturer, while the R_{total} was obtained by means of equation (A. 21). Capacitor C1 was obtained by placing capacitor C1' in series with C1''.

L (H)	0,119
C1' (F)	14×10^{-9}
C1'' (F)	$47{,}6 \times 10^{-9}$
C1 (F)	$10{,}8 \times 10^{-9}$
$R \pm \sigma_R(\Omega)$	3300$\pm$31
$R_L \pm \sigma_{R_L}(\Omega)$	65$\pm$1
$R_{total} \pm \sigma_{R_{total}}(\Omega)$	3302$\pm$31

Figures 12 show graphs that demonstrate how the gain of this circuit varies in relation to the frequency of the input signal. Having been obtained through the values contained in Table 31, present in the appendix.

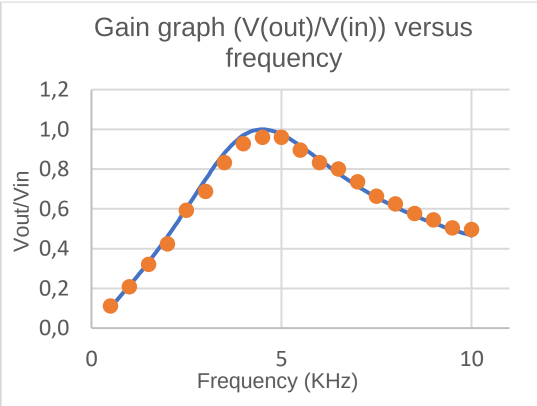

Figure 12: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points.

The values of the experimental resonance frequency (frequency at which the gain is maximum) and the theoretical values, obtained through equation (2), are presented in table 22, accompanied by the corresponding relative error.

Table 22: Values of the resonance frequency of this filter, experimental and theoretical. The uncertainty of the experimental value was estimated

at 5Hz due to the difficulty in identifying the exact frequency where the gain is maximum..

	Experi-mental	σ	Theore-tical	Error (%)
f_0 (Hz)	4600	5	4436	3,70
ω_0 (rad/s)	28903	32	27871	3,70

The values of the cutoff frequency, that is, the angular frequencies whose gain is equal to 1/√2, are presented in Table 23.

Table 23: Cutoff frequency values. The uncertainty of the experimental value was estimated at 5Hz due to the difficulty in identifying the exact frequency where the gain is 1/$\sqrt{2}$.

f1 (Hz)	2750 ± 5	ω1 (rad/s)	17279 ± 31
f2 (Hz)	7150 ± 5	ω2 (rad/s)	44925 ± 31

In Table 24, the experimental and theoretical bandwidth values, represented as β, calculated respectively by equations (3) and (5). Additionally, the values of the experimental and theoretical quality factors, indicated with Q, are also presented in this table, having been obtained by equations (4) and (6). The relative error values for both data sets are also presented in this table.

Table 24: Experimental and theoretical values of bandwidth, β, and quality factor, Q. The uncertainty of the experimental values was calculated using equation (A. 16) and (A. 17) in the appendix..

	Experi-mental	σ	Theore-tical	Error (%)
β (rad/s)	27646	45	28013	1,31
Q	1,05	0,01	1,00	5,07

4. Discussion of results and conclusion

Analyzing the graphs obtained from the frequency response we can conclude that both the RLC circuit in series and in parallel can serve as band-pass filters, that is, they allow the passage of frequencies within a certain range and reject the remaining ones.

Analyzing the series RLC circuit, we were able to verify what was predicted by the expression $\beta = \frac{R}{L}$ that the bandwidth is directly proportional to the value of the resistance used, however the quality factor Q is inversely proportional to the value of the resistance according to the expression $Q = \frac{1}{R}\sqrt{\frac{L}{C}}$ and the resonance frequency ω_0 does not change according to the expression $\omega_0 = \frac{1}{\sqrt{LC}}$. Varying the capacitance of the capacitor does not interfere with the bandwidth β as it is inversely proportional to the resonance frequency ω_0 and the quality factor Q. We also know from the expressions that the inductance of the coil is inversely proportional to the bandwidth β and the resonance frequency ω_0 and directly proportional to the quality factor Q.

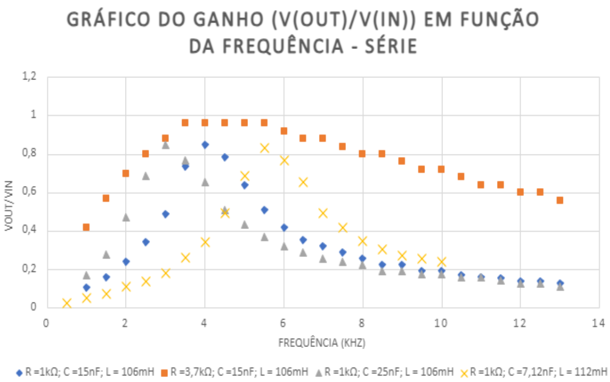

Figure 13: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points for various values of resistance, capacitor capacities and coil inductances in the series RLC circuit.

When comparing the theoretical and experimental values of the resonance frequency ω_0 we observe an agreement between them with an error of approximately 0%, but in relation to the bandwidth β and the quality factor Q there is a discrepancy between the theoretical and experimental values, in some cases greater than 20%, due to small experimental errors together with the fact that the resistance used is quite high which leads to very large values for the bandwidth β and very small for the quality factor Q, so in order to achieve more accurate results measurements of the output voltage should have been carried out in a wider range of frequencies, that is, larger and more spaced values in a more comprehensive way.

For the parallel RLC circuit we verify the veracity of the following expression $\beta = \frac{1}{RC}$ because we observe that the resistance value is inversely proportional to the bandwidth β and on the contrary directly proportional to the quality factor Q which is given by the following expression $Q = R\sqrt{\frac{C}{L}}$, the resonance frequency ω_0 is not altered by the resistance value according to the same expression used for the series RLC circuit $\omega_0 = \frac{1}{\sqrt{LC}}$. By varying the capacitance of the capacitor we verify that this variation is directly proportional to the quality factor Q but inversely proportional to the resonance frequency ω_0 and the bandwidth β. Once again, varying the value of the coil inductance we know that this variation is inversely proportional to the quality factor Q and the resonance frequency ω_0 and that it does not change the bandwidth β.

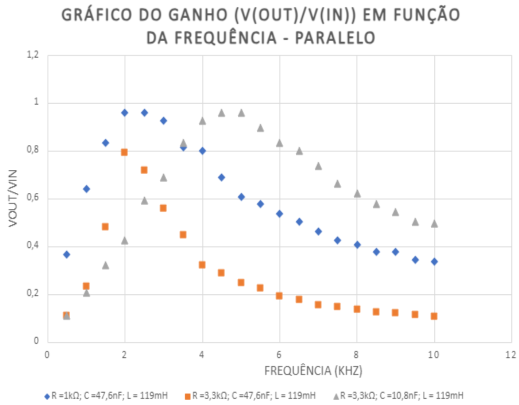

Figure 14: Representation of the experimental points of the gain as a function of frequency and the Gaussian function that best fits the experimental points for various values of resistance, capacitor capacities and inductances in the parallel RLC circuit.

When comparing the theoretical and experimental values of the resonance frequency ω_0, the bandwidth β and the quality factor Q, we find that they are all in agreement since the respective errors are mostly around 2%.

Overall, we can conclude that we were able to achieve values that were practically equal to those predicted theoretically, since the percentage error is quite small, with the exception of the values of the bandwidth β and the quality factor Q of the series RLC circuit, which leads us to conclude that we have good accuracy in our results.

Appendix

<u>Derivation equation of gain and phase difference between output and input signals is given for a series RLC circuit:</u>

Knowing that the impedance of the resistance is R, that of the capacitor is $\frac{1}{\omega C}j$ and the inductor is ωLj, then the total impedance of the circuit is given by:

$$Z = R + \left(\omega L - \frac{1}{\omega C}\right) j$$

i.e.:

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

So, we'll have to:

$$|v_{out}| = R\, I$$

$$|v_{in}| = |Z|\, I$$

That is, the gain is given by:

Ganho = $\left|\frac{v_{out}}{v_{in}}\right| = \frac{R\, I}{|Z|\, I} = \frac{R}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$ (A.1)

and the phase difference between the output and input signals is given by:

$$\tan(\theta) = \frac{Im(Z)}{Re(Z)}$$

$$\Leftrightarrow \theta = \arctan\left(\frac{\omega L - \frac{1}{\omega C}}{R}\right) \qquad \text{(A.2)}$$

<u>Derivation equation of gain and phase difference between output and input signals is given for a parallel RLC circuit:</u>

Knowing that the impedance of the resistance is R, that of the capacitor is $\frac{1}{\omega C} j$ and the inducto ris ωLj, then the total impedance of the circuit Z is given by:

$$Z = R + Z'$$

where Z' is the impedance of the inductor in parallel with the capacitor.

$$Z' = \frac{1}{\omega C j + \frac{1}{\omega L j}} = \frac{\omega L j}{1 - \omega^2 LC}$$

and

$$|Z'| = \left|\frac{\omega L}{1 - \omega^2 LC}\right|$$

Therefore, we have that:

$$Z = R + \frac{\omega L j}{1 - \omega^2 LC}$$

i.e.:

$$|Z| = \sqrt{R^2 + \left(\frac{\omega L}{1 - \omega^2 LC}\right)^2}$$

So, we'll have to:

$$|v_{out}| = |Z'| I$$

$$|v_{in}| = |Z|\, I$$

That is, the gain is given by:

Gain = $\left|\frac{v_{out}}{v_{in}}\right| = \frac{|Z'|\, I}{|Z|\, I} = \frac{\frac{\omega L}{1-\omega^2 LC}}{\sqrt{R^2 + \left(\frac{\omega L}{1-\omega^2 LC}\right)^2}}$

$$= \frac{\frac{\omega}{RC}}{\sqrt{\left(\frac{1}{LC} - \omega^2\right)^2 + \left(\frac{\omega}{RC}\right)^2}} \qquad \text{(A.3)}$$

and the phase difference between the output and input signals is given by:

$$\tan(\theta) = \frac{Im(Z)}{Re(Z)}$$

$$\Leftrightarrow \theta = \arctan\left(\frac{\frac{\omega L}{1-\omega^2 LC}}{R}\right) \qquad \text{(A.4)}$$

<u>Demonstration of resonance frequency:</u>

How does the total reactance cancel out in the resonance situation and how $Z_L = j\omega L$ and $Z_C = \frac{1}{j\omega C}$, then we have that the resonance frequency is given by:

$$Z_L + Z_C = 0 \Leftrightarrow j\omega L + \frac{1}{j\omega C} = 0$$

$$\Leftrightarrow \; j\omega L = -\frac{1}{j\omega C} \Leftrightarrow \omega L = \frac{1}{\omega C}$$

$$\Leftrightarrow \omega^2 = \frac{1}{LC} \Leftrightarrow \omega = \frac{1}{\sqrt{LC}} \qquad \text{(A.5)}$$

Therefore, the resonance frequency is given by $\omega_0 = \frac{1}{\sqrt{LC}}$.

Proof for β and Q of a series RLC circuit:

It is known that the gain for this type of circuit is given by equation (A. 1):

$$G = \frac{R}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

To find the respective cutoff frequencies, you have to do $G = \frac{1}{\sqrt{2}}$. Therefore, from here we have that:

$$\omega_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \left(\frac{1}{LC}\right)} \qquad \text{(A.6)}$$

$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \left(\frac{1}{LC}\right)} \qquad \text{(A.7)}$$

Now, how $\beta = \omega 2 - \omega 1$, then the bandwidth can also be calculated by the following expression:

$$\beta = \frac{R}{L} \qquad \text{(A.8)}$$

and as the quality factor is also given by $Q = \omega_0/\beta$, replacing β we have that:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \qquad \text{(A.9)}$$

Proof for β and Q of a RLC parallel circuit:

It is known that the gain for this type of circuit is given by equation (A. 3):

$$G = \frac{\frac{\omega}{RC}}{\sqrt{\left(\frac{1}{LC} - \omega^2\right)^2 + \left(\frac{\omega}{RC}\right)^2}}$$

To find the respective cutoff frequencies, you have to do $G = \frac{1}{\sqrt{2}}$. Therefore, from here we have that:

$$\omega_1 = -\frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 + \left(\frac{1}{LC}\right)} \qquad \text{(A.10)}$$

$$\omega_2 = \frac{1}{2RC} + \sqrt{\left(\frac{1}{2RC}\right)^2 + \left(\frac{1}{LC}\right)} \qquad \text{(A.11)}$$

Now, how $\beta = \omega 2 - \omega 1$, then the bandwidth can also be calculated by the following expression:

$$\beta = \frac{1}{RC} \qquad \text{(A.12)}$$

and as the quality factor is also given by $Q = \omega_0/\beta$, replacing β we have that:

$$Q = R\sqrt{\frac{C}{L}} \qquad \text{(A.13)}$$

Derivation of equations for calculating uncertainties:

The expression for the gain uncertainty was determined by applying the general expression for the propagation of uncertainties to the expression $G = \frac{V_{out}}{V_{in}}$:

$$(\sigma_G)^2 = \left(\frac{\partial G}{\partial V_{out}}\right)^2 \left(\sigma_{V_{out}}\right)^2 + \left(\frac{\partial G}{\partial V_{in}}\right)^2 \left(\sigma_{V_{in}}\right)^2$$

$$(=) \; (\sigma_G)^2 = \left(\frac{\sigma_{V_{out}}}{V_{in}}\right)^2 + \left(\frac{V_{out} \; \sigma_{V_{in}}}{V_{in}^2}\right)^2$$

$$(=)\ \sigma_G = G\sqrt{\left(\frac{\sigma_{V_{out}}}{V_{out}}\right)^2 + \left(\frac{\sigma_{V_{in}}}{V_{in}}\right)^2} \quad \text{(A.14)}$$

The expression for the uncertainty of the angular resonance frequency was determined by applying the general expression for the propagation of uncertainties to the expression $\omega_0 = 2\,\pi\,f_0$:

$$\left(\sigma_{\omega_0}\right)^2 = \left(\frac{\partial \omega_0}{\partial f_0}\right)^2 \left(\sigma_{f_0}\right)^2$$

$$(=)\ \sigma_{\omega_0} = 2\,\pi\,\sigma_{f_0} \quad \text{(A.15)}$$

The expression for the experimental bandwidth uncertainty, β, was determined by applying the general expression for the propagation of uncertainties to equation (3):

$$\left(\sigma_\beta\right)^2 = \left(\frac{\partial \beta}{\partial \omega_1}\right)^2 \left(\sigma_{\omega_1}\right)^2 + \left(\frac{\partial \beta}{\partial \omega_2}\right)^2 \left(\sigma_{\omega_2}\right)^2$$

$$(=)\ \sigma_\beta = \sqrt{\left(\sigma_{\omega_1}\right)^2 + \left(\sigma_{\omega_2}\right)^2} \quad \text{(A.16)}$$

The expression for the uncertainty of the experimental quality factor, Q, was determined by applying the general expression for the propagation of uncertainties to equation (4):

$$\left(\sigma_Q\right)^2 = \left(\frac{\partial Q}{\partial \omega_0}\right)^2 \left(\sigma_{\omega_0}\right)^2 + \left(\frac{\partial Q}{\partial \beta}\right)^2 \left(\sigma_\beta\right)^2$$

$$(=)\ \left(\sigma_Q\right)^2 = \left(\frac{\sigma_{\omega_0}}{\beta}\right)^2 + \left(\frac{\omega_0\ \sigma_\beta}{\beta^2}\right)^2$$

$$(=)\ \sigma_Q = Q\sqrt{\left(\frac{\sigma_{\omega_0}}{\omega_0}\right)^2 + \left(\frac{\sigma_\beta}{\beta}\right)^2} \quad \text{(A.17)}$$

Derivation of the equations for calculating the equivalent resistance of the circuit when considering the internal resistance of the inductor:

Expression for calculating the resistance of the series RLC circuit when considering the internal resistance of the coil, and the expression of its uncertainty obtained through the general expression of the propagation of uncertainties:

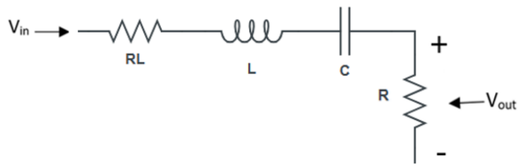

Figure 15: RLC circuit in series with inductorl resistance.

$$\bar{z} = R_L + R + \omega L j + \frac{1}{\omega C j}$$

Since, at the resonance frequency the complex part is 0, then the total resistance is given by:

$$R_{total} = R_L + R \quad \text{(A.18)}$$

The expression for the uncertainty of the total resistance is given by:

$$\left(\sigma_{R_{total}}\right)^2 = \left(\frac{\partial R_{total}}{\partial R_L}\right)^2 \left(\sigma_{R_L}\right)^2 + \left(\frac{\partial R_{total}}{\partial R}\right)^2 \left(\sigma_R\right)^2$$

$$(=)\ \sigma_{R_{total}} = \sqrt{\left(\sigma_{R_L}\right)^2 + \left(\sigma_R\right)^2} \quad \text{(A.19)}$$

Expression for calculating the resistance of the parallel RLC circuit when considering the internal resistance of the coil, and the expression of its uncertainty obtained through the general expression of the propagation of uncertainties:

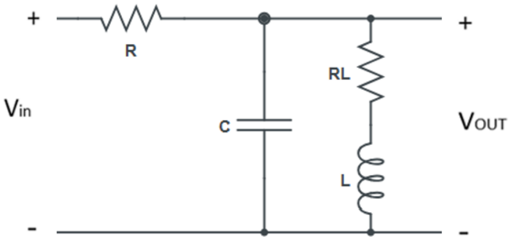

Figure 16: RLC circuit in parallel with inductor resistance.

$$\bar{z} = R + \frac{1}{\frac{1}{R_L + \omega L j} + \omega C}$$

Since, at the resonance frequency the imaginary part is 0, then the total resistance is given by:

$$R_{total} = R + \frac{R_L}{(1-\omega^2 LC)^2 + (RL\omega C)^2} \quad \text{(A.20)}$$

The expression for the uncertainty of the total resistance is given by:

$$(\sigma_{R_{total}})^2 = \left(\frac{\partial R_{total}}{\partial R}\right)^2 (\sigma_R)^2 + \left(\frac{\partial R_{total}}{\partial R_L}\right)^2 (\sigma_{R_L})^2$$

$$(=)\ \sigma_{R_{total}} = \sqrt{(\sigma_R)^2 + \frac{(1-\omega^2 LC)^2 - (RL\omega C)^2}{\left((1-\omega^2 LC)^2 + (RL\omega C)^2\right)^2} (\sigma_{R_L})^2} \quad \text{(A.21)}$$

Table 25 shows the values of the measurements of the frequency and amplitude of the output signal for the series RLC circuit, assembled with the components indicated in Table 1. The value of the voltage gain for each of the frequencies is also indicated.

Table 25: Values of the amplitude of the output signal, Vout, for each of the input signal frequencies. And the voltage gain,

Vout/Vin , for each of the frequencies. The frequency uncertainty and Vout were estimated at the resolution of the oscilloscope measurements.

The uncertainty of Vout/Vin was obtained using equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
1,000	0,001	0,52	0,01	0,104	0,002
1,500	0,001	0,80	0,01	0,160	0,002
2,000	0,001	1,20	0,01	0,240	0,002
2,500	0,001	1,72	0,01	0,344	0,002
3,000	0,001	2,45	0,01	0,490	0,002
3,500	0,001	3,68	0,01	0,736	0,002
4,000	0,001	4,24	0,01	0,848	0,003
4,500	0,001	3,92	0,01	0,784	0,003
5,000	0,001	3,20	0,01	0,640	0,002
5,500	0,001	2,56	0,01	0,512	0,002
6,000	0,001	2,08	0,01	0,416	0,002
6,500	0,001	1,76	0,01	0,352	0,002
7,000	0,001	1,60	0,01	0,320	0,002
7,500	0,001	1,44	0,01	0,288	0,002
8,000	0,001	1,28	0,01	0,256	0,002
8,500	0,001	1,12	0,01	0,224	0,002
9,000	0,001	1,12	0,01	0,224	0,002
9,500	0,001	0,96	0,01	0,192	0,002
10,000	0,001	0,96	0,01	0,192	0,002
10,500	0,001	0,84	0,01	0,168	0,002
11,000	0,001	0,80	0,01	0,160	0,002
11,500	0,001	0,76	0,01	0,152	0,002
12,000	0,001	0,70	0,01	0,140	0,002
12,500	0,001	0,68	0,01	0,136	0,002
13,000	0,001	0,64	0,01	0,128	0,002

Table 26 shows the values of the measurements of the frequency and amplitude of the output signal for the series RLC circuit, assembled with the components indicated in Table 5. The value of the voltage gain for each of the frequencies is also indicated.

Table 26: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The

uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
1,000	0,001	2,08	0,01	0,416	0,002
1,500	0,001	2,84	0,01	0,568	0,002
2,000	0,001	3,48	0,01	0,696	0,002
2,500	0,001	4,00	0,01	0,800	0,002
3,000	0,001	4,40	0,01	0,880	0,002
3,500	0,001	4,80	0,01	0,960	0,002
4,000	0,001	4,80	0,01	0,960	0,002
4,500	0,001	4,80	0,01	0,960	0,002
5,000	0,001	4,80	0,01	0,960	0,002
5,500	0,001	4,80	0,01	0,960	0,002
6,000	0,001	4,60	0,01	0,920	0,002
6,500	0,001	4,40	0,01	0,880	0,002
7,000	0,001	4,40	0,01	0,880	0,002
7,500	0,001	4,20	0,01	0,840	0,002
8,000	0,001	4,00	0,01	0,800	0,002
8,500	0,001	4,00	0,01	0,800	0,002
9,000	0,001	3,80	0,01	0,760	0,002
9,500	0,001	3,60	0,01	0,720	0,002
10,000	0,001	3,60	0,01	0,720	0,002
10,500	0,001	3,40	0,01	0,680	0,002
11,000	0,001	3,20	0,01	0,640	0,002
11,500	0,001	3,20	0,01	0,640	0,002
12,000	0,001	3,00	0,01	0,600	0,002
12,500	0,001	3,00	0,01	0,600	0,002
13,000	0,001	2,80	0,01	0,560	0,002

Table 27 shows the values of the frequency and amplitude measurements of the output signal for the series RLC circuit, assembled with the components shown in Table 9, using capacitor C1. The voltage gain value for each frequency is also indicated.

Table 27: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
1,000	0,001	0,84	0,01	0,168	0,002
1,500	0,001	1,40	0,01	0,280	0,002
2,000	0,001	2,36	0,01	0,472	0,002
2,500	0,001	3,44	0,01	0,688	0,002
3,000	0,001	4,24	0,01	0,848	0,002
3,500	0,001	3,84	0,01	0,768	0,002
4,000	0,001	3,28	0,01	0,656	0,002
4,500	0,001	2,56	0,01	0,512	0,002
5,000	0,001	2,16	0,01	0,432	0,002
5,500	0,001	1,84	0,01	0,368	0,002
6,000	0,001	1,60	0,01	0,320	0,002
6,500	0,001	1,44	0,01	0,288	0,002
7,000	0,001	1,28	0,01	0,256	0,002
7,500	0,001	1,20	0,01	0,240	0,002
8,000	0,001	1,12	0,01	0,224	0,002
8,500	0,001	0,96	0,01	0,192	0,002
9,000	0,001	0,96	0,01	0,192	0,002
9,500	0,001	0,88	0,01	0,176	0,002
10,000	0,001	0,88	0,01	0,176	0,002
10,500	0,001	0,80	0,01	0,160	0,002
11,000	0,001	0,80	0,01	0,160	0,002
11,500	0,001	0,72	0,01	0,144	0,002
12,000	0,001	0,64	0,01	0,128	0,002
12,500	0,001	0,64	0,01	0,128	0,002
13,000	0,001	0,56	0,01	0,112	0,002

Table 28 shows the values of the frequency and amplitude measurements of the output signal for the series RLC circuit, assembled with the components shown in Table 9, using capacitor C2. The voltage gain value for each frequency is also indicated.

Table 28: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The

uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
1,000	0,001	0,12	0,01	0,023	0,002
1,500	0,001	0,25	0,01	0,050	0,002
2,000	0,001	0,38	0,01	0,076	0,002
2,500	0,001	0,55	0,01	0,110	0,002
3,000	0,001	0,70	0,01	0,140	0,002
3,500	0,001	0,90	0,01	0,180	0,002
4,000	0,001	1,32	0,01	0,264	0,002
4,500	0,001	1,70	0,01	0,340	0,002
5,000	0,001	2,48	0,01	0,496	0,002
5,500	0,001	3,44	0,01	0,688	0,002
6,000	0,001	4,16	0,01	0,832	0,002
6,500	0,001	3,84	0,01	0,768	0,002
7,000	0,001	3,28	0,01	0,656	0,002
7,500	0,001	2,48	0,01	0,496	0,002
8,000	0,001	2,08	0,01	0,416	0,002
8,500	0,001	1,75	0,01	0,350	0,002
9,000	0,001	1,52	0,01	0,304	0,002
9,500	0,001	1,36	0,01	0,272	0,002
10,000	0,001	1,28	0,01	0,256	0,002
1,000	0,001	1,20	0,01	0,240	0,002

Table 29 presents the values of the measurements of the frequency and amplitude of the output signal for the parallel RLC circuit, assembled with the components indicated in Table 13. The value of the voltage gain for each of the frequencies is also indicated.

Table 29: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
0,500	0,001	1,84	0,01	0,368	0,002
1,000	0,001	3,20	0,01	0,640	0,002
1,500	0,001	4,16	0,01	0,832	0,002
2,000	0,001	4,80	0,01	0,960	0,002
2,500	0,001	4,80	0,01	0,960	0,002
3,000	0,001	4,64	0,01	0,928	0,002
3,500	0,001	4,08	0,01	0,816	0,002
4,000	0,001	4,00	0,01	0,800	0,002
4,500	0,001	3,44	0,01	0,688	0,002
5,000	0,001	3,04	0,01	0,608	0,002
5,500	0,001	2,88	0,01	0,576	0,002
6,000	0,001	2,68	0,01	0,536	0,002
6,500	0,001	2,52	0,01	0,504	0,002
7,000	0,001	2,32	0,01	0,464	0,002
7,500	0,001	2,12	0,01	0,424	0,002
8,000	0,001	2,04	0,01	0,408	0,002
8,500	0,001	1,88	0,01	0,376	0,002
9,000	0,001	1,88	0,01	0,376	0,002
9,500	0,001	1,72	0,01	0,344	0,002
10,000	0,001	1,68	0,01	0,336	0,002

Table 30 shows the values of the measurements of the frequency and amplitude of the output signal for the parallel RLC circuit, assembled with the components indicated in Table 30. The value of the voltage gain for each of the frequencies is also indicated.

Table 30: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$

0,500	0,001	0,56	0,01	0,112	0,002
1,000	0,001	1,16	0,01	0,232	0,002
1,500	0,001	2,40	0,01	0,480	0,002
2,000	0,001	3,96	0,01	0,792	0,002
2,500	0,001	3,60	0,01	0,720	0,002
3,000	0,001	2,80	0,01	0,560	0,002
3,500	0,001	2,24	0,01	0,448	0,003
4,000	0,001	1,60	0,01	0,320	0,003
4,500	0,001	1,44	0,01	0,288	0,002
5,000	0,001	1,24	0,01	0,248	0,002
5,500	0,001	1,12	0,01	0,224	0,002
6,000	0,001	0,96	0,01	0,192	0,002
6,500	0,001	0,88	0,01	0,176	0,002
7,000	0,001	0,78	0,01	0,156	0,002
7,500	0,001	0,74	0,01	0,148	0,002
8,000	0,001	0,68	0,01	0,136	0,002
8,500	0,001	0,63	0,01	0,126	0,002
9,000	0,001	0,60	0,01	0,120	0,002
9,500	0,001	0,57	0,01	0,114	0,002
10,000	0,001	0,54	0,01	0,108	0,002

Table 31 presents the values of the measurements of the frequency and amplitude of the output signal for the parallel RLC circuit, assembled with the components indicated in Table 21. The value of the voltage gain for each of the frequencies is also indicated.

Table 31: Output signal amplitude values, V_{OUT}, for each of the input signal frequencies. And the voltage gain, $\frac{V_{OUT}}{V_{IN}}$, for each of the frequencies. The uncertainty of frequency and V_{OUT} were estimated at the resolution of the oscilloscope measurements. The uncertainty of $\frac{V_{OUT}}{V_{IN}}$ was obtained through the equation (A. 14).

F (KHz)	σ_F (KHz)	V_{OUT} (V)	$\sigma_{V_{OUT}}$ (V)	$\frac{V_{OUT}}{V_{IN}}$	$\sigma_{\frac{V_{OUT}}{V_{IN}}}$
0,500	0,001	0,56	0,01	0,111	0,002
1,000	0,001	1,04	0,01	0,208	0,002
1,500	0,001	1,60	0,01	0,320	0,002
2,000	0,001	2,12	0,01	0,424	0,002
2,500	0,001	2,96	0,01	0,592	0,002
3,000	0,001	3,44	0,01	0,688	0,002
3,500	0,001	4,16	0,01	0,832	0,003
4,000	0,001	4,64	0,01	0,928	0,003
4,500	0,001	4,80	0,01	0,960	0,002
5,000	0,001	4,80	0,01	0,960	0,002
5,500	0,001	4,48	0,01	0,896	0,002
6,000	0,001	4,16	0,01	0,832	0,002
6,500	0,001	4,00	0,01	0,800	0,002
7,000	0,001	3,68	0,01	0,736	0,002
7,500	0,001	3,32	0,01	0,664	0,002
8,000	0,001	3,12	0,01	0,624	0,002
8,500	0,001	2,88	0,01	0,576	0,002
9,000	0,001	2,72	0,01	0,544	0,002
9,500	0,001	2,52	0,01	0,504	0,002
10,000	0,001	2,48	0,01	0,496	0,002

Bibliography

[1] The RLC circuit as a frequency filter (series and parallel), Practical Guide provided by the teacher.

[2] FLUKE Models 177 True RMS Multimeters.