Lab 7 - AC Currents & Voltage

OBJECTIVES

- To understand the meanings of amplitude, frequency, phase, reactance, and impedance in AC circuits.
- To observe the behavior of resistors in AC circuits.
- To observe the behaviors of capacitors and inductors in AC circuits.
- To examine the resonant behavior of RLC series circuits.

OVERVIEW

Until now, you have investigated electric circuits in which a battery provided an input voltage that was effectively constant in time. This is called a DC or Direct Current signal. A steady voltage applied to a circuit eventually results in a steady current. Steady voltages are usually called DC voltages as shown in Figure 7.1.

Signals that change over time (see Figure 7.2) exist all around you, and many of these signals change in a regular manner. For example, the electrical signals produced by your beating heart change continuously in time.

There is a special class of time-varying signals. These signals can be used to drive current in one direction in a circuit, then in the other direction, then back in the original direction, and so on. They are referred to as AC or Alternating Current signals as seen in Figure 7.3.
It can be shown that any periodic signal can be represented as a sum of weighted sines and cosines (known as a *Fourier series*). It can also be shown that the response of a circuit containing resistors, capacitors, and inductors (an “RLC” circuit) to such a signal is simply the sum of the responses of the circuit to each sine and cosine term with the same weights. We further note that a cosine is just a sine that is shifted back in time by $1/4$ cycle (a phase shift of $-90^\circ$ or $-\pi/2$ radians). So, to analyze an RLC circuit we need only find the response of the circuit to an input sine wave of arbitrary frequency.

Let us suppose that we have found a way to generate an input current of the form:

$$I(t) = I_{\text{max}} \sin(\omega t)$$  \hspace{1cm} (7.1)

*Note:* Here we use the *angular frequency*, $\omega$, which has units of radians per second. Most instruments report, $f$, which has units of cycles per second or Hertz (Hz). Clearly, $\omega = 2\pi f$.

We have already seen that the voltage across a resistor is then given by:

$$V_{R}(t) = RI_{\text{max}} \sin(\omega t)$$  \hspace{1cm} (7.2)

Without proof we will state that the voltage across a capacitor is given by:
\[ V_C(t) = -\frac{I_{\text{max}}}{\omega C} \cos(\omega t) = \frac{I_{\text{max}}}{\omega C} \sin\left(\omega t - \frac{\pi}{2}\right) \]  
(7.3)

and the voltage across an inductor is given by:

\[ V_L(t) = \omega L I_{\text{max}} \cos(\omega t) = \omega L I_{\text{max}} \sin\left(\omega t + \frac{\pi}{2}\right) \]  
(7.4)

These can all be written in the form (a generalized Ohm’s Law):

\[ V(t) = I_{\text{max}} Z \sin(\omega t + \varphi) \]  
(7.5)

Arbitrary combinations of resistors, capacitors and inductors will have voltage responses of this form. \( Z \) is called the \textit{impedance} and \( \varphi \) is called the \textit{phase shift}. The maximum voltage will be given by

\[ V_{\text{max}} = I_{\text{max}} Z \]  
(7.6)

Consider a series circuit with a resistor, capacitor, and inductor as shown in Figure 7.4.

![Series circuit](image)

Figure 7.4: Series circuit of AC voltage and \( R, L, \) and \( C \)

The impedance for a \textit{RLC} series circuit is given by

\[ Z_{\text{series}} = \sqrt{R^2 + (X_L - X_C)^2} \]  
(7.7)

and the phase shift \( \varphi_{\text{series}} \) by

\[ \tan(\varphi_{\text{series}}) = \frac{X_L - X_C}{R} \]  
(7.8)

where

\[ X_C \equiv \frac{1}{\omega C} \]  
(7.9)

and

\[ X_L \equiv \omega L \]  
(7.10)

\( X_C \) is called the \textit{capacitive reactance} and \( X_L \) is called the \textit{inductive reactance}. If there is only a capacitor or only an inductor, the impedance is simply the corresponding reactance.
If we rearrange Equation (7.6) and solve for the current $I_{\text{max}}$, we have

$$I_{\text{max}} = \frac{V_{\text{max}}}{Z} \quad (7.11)$$

We obtain the maximum current with the impedance $Z$ is a minimum. If we examine Equation (7.6) we see that this occurs when $X_L = X_C$ or

$$\omega L = \frac{1}{\omega C} \quad \text{or} \quad \omega^2 = \frac{1}{LC} \quad (7.12)$$

The condition for resonance in an $RLC$ series circuit is then

$$\omega = \frac{1}{\sqrt{LC}} \quad \text{and} \quad f = \frac{1}{2\pi \sqrt{LC}} \quad (7.13)$$

In Investigation 1, you will explore how a time-varying signal affects a circuit with a resistor. In Investigations 2 and 3, you will explore how capacitors and inductors influence the current and voltage in various parts in an AC circuit. In Investigation 4, you will look at the resonance in an $RLC$ series circuit.

**INVESTIGATION 1: AC SIGNALS AND RESISTANCE**

In this investigation, you will consider the behavior of resistors in a circuit driven by AC signals of various frequencies.

You will need the following materials:

- current probe and voltage probe
- 100 $\Omega$ resistor
- multimeter
- alligator clip leads
- internal *Data Studio* signal generator

**Activity 1-1: Resistors and Time-Varying (AC) Signals**

Consider the circuit in Figure 7.5 with a signal generator and resistor.

![Figure 7.5](image_url)
**Question 1-1:** What is the relationship between the input signal, $V_{signal}$, and the voltage measured by the voltage probe, $V$? *(Hint: remember that CP$_A$ has a very small resistance compared to $R$).*

**Prediction 1-1: Do this before coming to lab.** On the axes that follow, sketch, with dotted lines, your qualitative prediction for the current $I$ through the resistor (100 $\Omega$) and the voltage across the resistor $V_R$ vs. time. *(Hint: consider Ohm’s Law). Assume $V_{signal}$ has frequency of 20 Hz and amplitude (peak voltage) of 5 V. Draw two complete periods and don’t forget to label your axes.*

![Graph](image.png)

Test your predictions.

1. Open the experiment file L07.A1-1 Resistor with AC.
2. Measure the resistance of the nominal 100 $\Omega$ resistor:

   $$R: \quad \text{\Omega}$$

3. Connect the circuit in Figure [7.5](#). Check SETUP. We are using the internal signal generator of the PASCO interface. The controls should appear on the computer screen.

4. Set the signal generator to 20 Hz and 5 volts amplitude (+5 V maximum and -5 V minimum). We call this 10 V peak-to-peak.
5. **Begin** graphing. When you have a good graph of the signal, **stop** graphing. Expand the graph to look at the two complete periods.

6. **Print** one set of graphs for your group report. Do not erase data.

7. On the printed graph of voltage vs. time, identify and label a time or two when the **current** through the resistor is maximum. Depending on the way you hooked up the voltage probe across the resistor, you may have current and voltage in or out of phase. If out of phase, you may want to switch the voltage probe and repeat.

8. On your graph of current vs. time, identify and label a time or two when the **voltage** across the resistor is maximum.

   **Question 1-2:** Does a voltage maximum occur at the same time as a current maximum, or does one maximum (current or voltage) occur before the other? Explain.

9. Use the **Smart Tool** to find the period (time from one peak to the next), $T$, of the voltage.

   $T$: _______________ s

10. Use your graph to complete Column I in Table [7.1]. To obtain information from the graph, you can use the **Smart Tool** or you can select several cycles by highlighting them, and then use the **statistics** feature to find the maximum values for the voltage and current.

11. Now set the frequency of the signal generator to 40 Hz. Check that the amplitude is still 5 V. **Graph I** and **V** as before. Use the **analysis** feature to complete Column II in Table [7.1]. Do not print out this graph.

   **Question 1-3:** Based on the calculations in Table [7.1], what can you say about the resistance of $R$ at different frequencies (does its value appear to increase, decrease, or stay the same as frequency increases)? Explain your answer.

**Question 1-4:** When the input signal is 40 Hz, does a maximum positive current through $R$ occur before, after, or at the same time as the maximum positive voltage across $R$?
<table>
<thead>
<tr>
<th>Column I</th>
<th>Column II</th>
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</thead>
<tbody>
<tr>
<td>$f = 20\text{Hz}$</td>
<td>$f = 40\text{Hz}$</td>
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<tr>
<td>At maximum voltage, current is (circle one): maximum, minimum, zero and increasing, zero and decreasing, nonzero and increasing, nonzero and decreasing, other</td>
<td>At maximum voltage, current is (circle one): maximum, minimum, zero and increasing, zero and decreasing, nonzero and increasing, nonzero and decreasing, other</td>
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<td>max. voltage ($V_{\text{max}}$)</td>
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<tr>
<td>max. current ($I_{\text{max}}$)</td>
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<tr>
<td>$R = \frac{V_{\text{max}}}{I_{\text{max}}}$</td>
<td>$R = \frac{V_{\text{max}}}{I_{\text{max}}}$</td>
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</tbody>
</table>

Table 7.1:

**Note:** Do not disconnect this circuit as you will be using a very similar one in Investigation 2.

**INVESTIGATION 2: AC SIGNALS WITH CAPACITORS**

You will need the following materials:

- current probe and voltage probe
- multimeter
- 47 $\mu$F capacitor
- seven alligator clip leads
- internal *Data Studio* signal generator

**Activity 2-1: Capacitors and AC Signals**

In this investigation we want to see how the impedance of a capacitor changes when the frequency of the applied signal changes. You will investigate this by measuring the behavior of a capacitor when signals of various frequencies are applied to it. Specifically, you will look at the amplitudes and the relative phase of the current through it and the voltage across it.

Consider the circuit shown in Figure 6.
Prediction 2-1: Suppose that you replaced the signal generator with a battery and a switch. The capacitor is initially uncharged, and therefore the voltage across the capacitor is zero. If you close the switch, which quantity reaches its maximum value first: a) current in the circuit or b) voltage across the capacitor? As charge builds up on the capacitor and the voltage across the capacitor increases, what happens to the current in the circuit? Explain. Do this before coming to lab.

Prediction 2-2: Do this before coming to lab. Sketch on the following axes one or two cycles of the current $I_C$ through the capacitor and the voltage $V_C$ across the capacitor versus time for the circuit in Figure 6. Use your answers to the previous prediction. Assume $V_{signal}$ has frequency of 20 Hz and amplitude of 5 V. Label your axes.
Test your predictions.

1. Open the experiment file called **L07.A2-1 Capacitor**.
2. Measure the capacitance of the capacitor:

   \[ C: \phantom{1} \mu\text{F} \]

3. Connect the circuit in Figure 7.6.
4. Set the signal generator to 20 Hz and amplitude of 5 Volts.
5. **Begin** graphing. When you have a good graph of the signal, **stop** graphing. Expand the graph to look at the same range as above.
6. **Print** one set of graphs for your group report.
7. On the graph of voltage vs. time, identify and label a time or two when the **current** through the capacitor is maximum.
8. On your graph of current vs. time, identify and label a time or two when the **voltage** across the capacitor is maximum.
9. Clearly mark one period of the AC signals on your graphs.

**Comment:** One way you can determine the phase difference between two sinusoidal graphs with the same period is by finding the time difference between peaks from each graph and dividing that time difference by the time period. This will give you the phase difference as a fraction of a period. In other words:

\[ \Delta\phi^\circ = 360^\circ \cdot f \cdot \Delta t \]

For example, if the time difference between two peaks is 0.5 s and the period of the signals is 2.0 s, then the phase difference is 0.25 or 1/4 period. Phase differences should be given in degrees or radians by simply multiplying the phase difference in periods by 360°/period or 2\pi rad/period. In this example, the signals are 90° or \pi/2 radians out of phase. The signal that reaches its peak first in time is said to **lead** the other.

**Question 2-1:** Discuss how well your measured voltage graph agrees with your predicted one.
<table>
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<tr>
<td>max current ($I_{\text{max}}$)</td>
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<tr>
<td>Experimental $Z = \frac{V_{\text{max}}}{I_{\text{max}}}$</td>
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<tr>
<td>Theoretical $Z \approx X_C = \frac{1}{\omega C}$</td>
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<td>Theoretical phase diff: _______ (deg)</td>
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<td>Experimental phase diff: _______ (deg)</td>
<td>Experimental phase diff: _______ (deg)</td>
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<tr>
<td>Current leads or voltage leads?</td>
<td>Current leads or voltage leads?</td>
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</table>

Table 7.2:

**Question 2-2:** For the capacitor with an input signal of 20 Hz, does a current maximum occur before, after, or at the same time as the maximum voltage?

**Question 2-3:** Calculate the theoretical phase difference between current and voltage for both 20 Hz and 40 Hz. Show your work and put your result in Table 7.2

10. Use the various analysis features to help you fill in Column I in Table 7.2. Determine the experimental phase difference.
11. Set the frequency of the signal generator to 40 Hz. Check that the amplitude is still 5 V. 
   **Graph** current \(I\) and voltage \(V\) as before. Use the **analysis feature** to complete Column II in Table 7.2. Do not print graph.

**Question 2-4:** Based on your observations, what can you say about the magnitude of the reactance of the capacitor at 20 Hz compared to the reactance of the capacitor at 40 Hz? Explain.

**Question 2-5:** Based on your observations, what can you say about the phase difference between current and voltage for a capacitor at 20 Hz compared to the phase difference at 40 Hz? Explain.

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**INVESTIGATION 3: AC SIGNALS WITH INDUCTORS**

In addition to the previous material, you will need:

- current probe and voltage probe
- multimeter
- 800 mH inductor
- seven alligator clip leads
- internal signal generator

**Activity 3-1: Inductors and AC Signals**

In this investigation we want to see how the impedance of an inductor changes when the frequency of the applied signal changes. We will follow much the same procedure as for the capacitor.

Consider the circuit shown in Figure 7.7.
Prediction 3-1: Suppose that you replaced the signal generator with a battery and a
switch. The inductor initially has no current through it. If you close the switch, which
quantity reaches its maximum value first: current in the circuit or voltage across the
inductor? [Hint: recall that when the current through an inductor is changing, the induced
voltage across the inductor opposes the change.] As the current builds up in the circuit,
what happens to the induced voltage across the inductor? Explain. Do this before coming
to lab.

Prediction 3-2: Sketch on the following axes one or two cycles of the current $I_L$ through
the inductor and the voltage $V_L$ across the inductor versus time for the circuit in Figure 6.
Use your answers to the previous prediction. Assume $V_{signal}$ has frequency of 20 Hz and
amplitude of 5 V. Label your axes. Do this before coming to lab. Your TA will check.
Test your predictions.

1. Open the experiment file called **L07.A3-1 Inductor**.

2. Measure the inductance of the inductor:

   \[
   L: \quad \text{___________ mH}
   \]

   **Note:** The internal series resistance of the inductor is *not* negligible at these low frequencies. Hence we can not approximate the impedance \( Z \) by the reactance \( X \) as we did in the case of the capacitor, but we must include the effect of the resistance when considering the impedance.

3. Measure the resistance of the inductor:

   \[
   R: \quad \text{___________ } \Omega
   \]

4. Connect the circuit in Figure 7.7.

5. Set the signal generator to 20 Hz and amplitude of 5 volts (+5 V maximum and -5 V minimum).

6. **Begin** graphing. When you have a good graph of the signal, **stop** graphing. Expand the graph to look at the same range as above.

7. **Print** one set of graphs for your group report.

8. On your graph of voltage vs. time, identify and label two times when the **current** through the inductor is maximum.

9. On your graph of current vs. time, identify and label two times when the **voltage** across the inductor is maximum.

10. Clearly mark one period of the AC signals on your graphs.

   **Question 3-1:** Does your measured voltage graph agree with your predicted one? If not, how do they differ?
**Question 3-2:** For the inductor with an input signal of 20 Hz, does a current maximum occur before, after, or at the same time as the maximum voltage? Explain.

11. Use the analysis features to fill in Column I in Table 7.3.

12. Set the frequency of the signal generator to 40 Hz. Check that the amplitude is still 5 V. **Graph** *I* and *V* as before. Use the analysis features to complete Column II in Table 7.3. **Do not print graph.**

**Question 3-3:** Calculate the theoretical phase difference between current and voltage for both 20 Hz and 40 Hz. Show your work and put your result in Table 7.3.

**Question 3-4:** What can you say about the magnitude of the reactance of the inductor at 20 Hz compared to the reactance of the inductor at 40 Hz? Explain based on your observations.

**Question 3-5:** Based on your observations, what can you say about the phase difference between current and voltage for an inductor at 20 Hz compared to the phase difference at 40 Hz? Explain. Were the phase differences what you expected? Do you think the fact that the inductor you used has a significant resistance plays a role?

**Question 3-6:** Discuss the agreement between your experimental impedances with theoretical impedances [Tables 7.2 and 7.3].

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**INVESTIGATION 4: THE SERIES RLC RESONANT CIRCUIT**
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<td>max voltage ($V_{\text{max}}$)</td>
<td>max voltage ($V_{\text{max}}$)</td>
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<td>Experimental phase diff: _______ (deg)</td>
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<tr>
<td>Current leads or voltage leads?</td>
<td>Current leads or voltage leads?</td>
</tr>
</tbody>
</table>

Table 7.3:

In this investigation, you will use your knowledge of the behavior of resistors, capacitors and inductors in circuits driven by various AC signal frequencies to predict and then observe resonant behavior in a series $RLC$ circuit.

The $RLC$ series circuit you will study in this investigation exhibits a “resonance” behavior that is useful for many familiar applications. One of the most familiar uses of such a circuit is as a tuner in a radio or television receiver. Hence, this is sometimes called a tuner circuit.

You will need the following materials:

- voltage probe
- $RLC$ Circuit Board

Consider the series $RLC$ circuit shown in Figure 7.8 (below).

NOTE: Do not yet set up the circuit in Figure 7.8
Nominal values:

\[ R = 10 \, \Omega \]
\[ L = 8.2 \, \text{mH} \]
\[ C = 1.2 \, \mu\text{F} \]

Figure 7.8: Series RLC circuit. We measure the current by observing the voltage across a resistor. The AC voltage driving the circuit \( V_{\text{signal}} \) has the frequency \( f \).

**Prediction 4-1:** Consider the circuit shown in Figure 7.8. At very low signal frequencies (near 0 Hz), will the maximum values of \( I \) through the resistor and \( V \) across the resistor be relatively large, intermediate or small compared to other elements in the circuit? Explain your reasoning. Do this before coming to lab.

**Prediction 4-2:** Consider the circuit shown in Figure 7.8. At very high signal frequencies (well above 3,000 Hz), will the maximum values of \( I \) and \( V \) across the resistor be relatively large, intermediate or small compared to other elements in the circuit? Explain your reasoning. Do this before coming to lab.

**Prediction 4-3:** Based on your Predictions 4-1 and 4-2, is there some intermediate frequency where \( I \) and \( V \) will reach maximum or minimum values? Do you think they will be maximum or minimum? Do this before coming to lab.

**Prediction 4-4:** On the axes below, draw qualitative graphs of \( X_C \) vs. frequency and \( X_L \) vs. frequency \( f \) of the AC applied voltage. Clearly label each curve. You may need to go back and look at Equations (7.9) and (7.10). Do this before lab.
**Question 4-1:** For what relative values of $X_L$ and $X_C$ will the total impedance of the circuit, $Z$, be a minimum? Hint: see Equation (7.7). Explain your reasoning here.

On the axes above, mark and label the frequency where $Z$ is a minimum.

**Question 4-2:** At the frequency you labeled, will the value of the peak current, $I_{\text{max}}$, in the circuit be a maximum or minimum? What about the value of the peak voltage, $V_R$, across the resistor? Explain.

**Note:** The point you identified in step 1 is the resonant frequency. Label it with the symbol $f_0$. The resonant frequency is the frequency at which the impedance of the series combination of a resistor, capacitor and inductor is minimal. This occurs at a frequency where the values of $X_L$ and $X_C$ are equal.

**Activity 4-1: The Resonant Frequency of a Series RLC Circuit.**

1. Open the experiment file **L07.A4-1 RLC Resonance**.

2. Note that the $V_R$ scope scale is 0.1 V/div and 1 ms/div and the signal generator scale to 2 V/div. The signal generator will remain at a maximum voltage of 5 V with a frequency of 100 Hz for the entire experiment.
3. You will be finding the maximum resonant current in the circuit shown in Figure 7.8. Remember that the voltage across a resistor is directly proportional to the current through the resistor. So you will measure the voltage $V$ across the 10 $\Omega$ resistor to find the resonant frequency.

4. Before connecting the circuit shown in Figure 7.8 measure with your multimeter the isolated circuit board elements for the nominal values of $R$, $L$, $C$ given in Figure 7.8. Write down the measured values here along with their units.

   $R$ (resistor): \underline{______________} $\Omega$

   $L$: \underline{______________} mH  $R_{\text{inductor}}$: \underline{______________} $\Omega$

   $C$: \underline{______________} $\mu$F

5. Connect the circuit shown in Figure 7.8.

6. Calculate the expected resonant frequency of your circuit using the measured values of $R$, $L$, and $C$.

   $f_{\text{calc}}$: \underline{______________} Hz

7. Press On for the signal generator and Start to begin taking data.

8. Adjust the $V_R$ scope scale to see the $V_R$ signal. It is probably quicker to interpolate the vertical scale to obtain the maximum voltage, but you can use the Smart Tool.

9. Enter the data in Table 7.4.

10. Measure the voltage for the other frequencies in Table 7.4.

11. Now you should have a good idea of the value of the resonant frequency. If you have time, use steps of 50 Hz on either side of the suspected resonant frequency value and take voltage measurements for perhaps an additional 5 frequencies on each side of the suspected frequency. This should allow you to map out more precisely the resonant frequency.

12. Print out your data at the resonant frequency.

13. What is your experimental resonant frequency? Provide a rough estimate of the experimental error based on how precisely you can pinpoint the resonant frequency.

   $f_{\text{exp}}$: \underline{______________} $\pm$ \underline{______________} Hz
<table>
<thead>
<tr>
<th>$f_{\text{signal}}$ (Hz)</th>
<th>$V_R$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td></td>
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<tr>
<td>400</td>
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<tr>
<td>2500</td>
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<tr>
<td>2800</td>
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</tbody>
</table>

Table 7.4:

**Question 4-3:** How does this experimental value for the resonant frequency compare with your calculated one? Try to explain any differences greater than the estimated experimental error.

14. Go to Excel and produce a plot of your voltage measurement across the resistor (proportional to current) versus the input signal frequency.

15. Label and print out the plot for your group.

The plot you just produced should indicate the resonant behavior of a series $RLC$ circuit. It should be clear to you that by choosing various values of the individual values of $R$, $L$, and $C$
we can produce a circuit that passes signals of chosen frequencies. That is, the output voltage $V_{out}$ that we are measuring across the resistor is significant for only a narrow region around the resonant frequency. You can think of the circuit as filtering out unwarranted frequencies. It is called a *band-pass filter circuit*.

Please clean up your lab area