CRYSTAL RADIOS and LRC CIRCUITS - 1

PHYS 251 Laboratory

INTRODUCTION

Our goal is to understand the operation of a crystal radio which is basically an LRC circuit. This is a two part experiment. The emphasis during the first week is on resonance. During the following week, the actual crystal radio will be studied.

The crystal radio is almost a magical device. It contains no batteries or other power source, yet it produces sound. Where does the energy for the sound waves come from? Is there a free lunch? The energy comes from the radio transmitter. Capturing energy can be tricky. Consider a radio station that transmitter is producing 100,000 watts of radio waves and this power is radiated into a half sphere about the transmitter. If this station is 10 kilometers away (~7miles), then an antenna that is 10 meter (~10 yards) long would collect less than 1/1000th of a watt.
How can a crystal radio do this amazing feat? The secret is resonance. That is the current in the crystal radio circuit will naturally oscillate back and forth at the same frequency of the radio waves. Some intuition about oscillations and resonance can be gained by considering mechanical systems. (See the second page of this writeup for details on the analogy.)

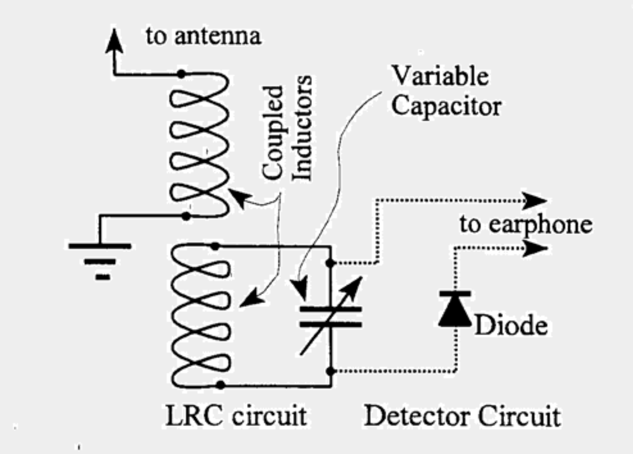


Figure 1 The circuit for a basic crystal radio.

Almost everyone has an intuitive understanding of the playground swing, and so it is a good first example. If the person in the swing is neither "pumping" nor being pushed, and if frictional losses are small, one has a simple harmonic oscillator. If the rider drags his or her feet then there is *damping* which is like resistance in a circuit. If someone is pushing the person in the swing, then there is an *external driving force.* Without thinking about it, the one pushing applies a driving force at the *resonant frequency* such that the swing goes fairly high even with relatively small pushes. If you were blindfolded and were pushing the swing based on the beat of the music on a radio, you would probably get out of time with the swing and eventually have a rather hard collision with the person in the swing. This is somewhat like what happens to LRC circuits that are driven at something other than their resonant frequency. (This is a very crude model of resonance but it may be useful, for developing an intuitive feel for resonance.)

A refinement of this model would be to replace conventional pushing of the swing with someone pulling on the swing using a weak long spring. Then not much force could be applied during any one cycle, but after many cycles the swing might be going quite high.

The general circuit for a crystal radio looks like that shown in fig. 1. In this circuit a commercial diode replaces the traditional diode made from a bit of germanium crystal and 'a cat's whisker contact.

The central portion of a crystal radio circuit is the LRC circuit. Even though there is no resistor in the circuit, the resistance of the wire especially the wire that makes up the inductor must be considered. This circuit is tuned so that its natural resonant frequency matches the frequency of the radio station that you want to hear. In the circuit in fig. 1, the capacitance of the variable capacitor is changed to tune the frequency. In other crystal radios a variable inductor is used for tuning.

How does the whole thing work? The radio transmitter produces waves of varying electric and magnetic fields. Basically the antennas at the transmitter and at the receiver are inductively coupled. These fields push or pull electrons in the antenna toward or away from the electrical ground. This produces a varying current through the inductor that connects the antenna to ground.

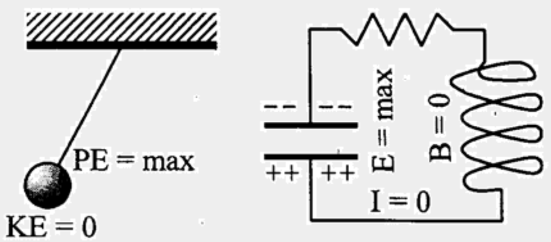
This inductor is coupled to the inductor in the LRC circuit and thus produces a voltage in this second inductor. (Often these two inductor not only use a common core but actually has much of the wire in common.) These two coupled inductors act as a transformer and this transformer is used to increase the voltage of the signal.

If the frequency of the signal exciting a current in the antenna matches the resonant frequency of the LRC circuit, the voltage and current in the LRC circuit will grow. Remember that for a typical AM radio frequency there are about a million cycles per second, so a little increase in the signal on each cycle can add up quickly. As this signal grows, the voltage across the capacitor will exceed the forward turn on voltage of the diode and current will flow through the earphone.

The analog between mechanical and electrical oscillators

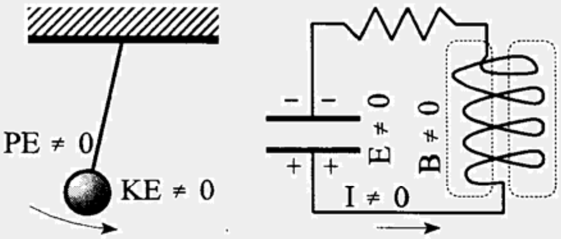
(a supplement)

Consider an LRC circuit that is oscillating with a period, T, and the cycle starts when there is no current ht the capacitor is charged. This state is analogous to the swing being at the highest point in it motion in the case of the swing there is no movement and no kinetic energy at this point in its cycle. For the LRC circuit all of its energy is stored in the capacitor's electric field.



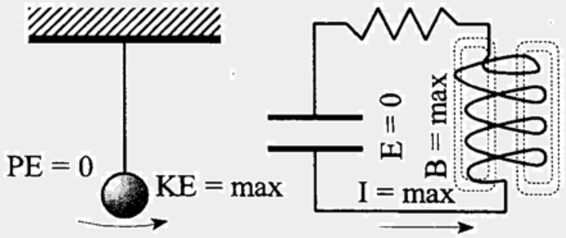
Time = 0

As the capacitor discharges, a current flows through the inductor thus creating a magnetic field. Energy is being converted from the electric field in the capacitor to the magnetic field of the inductor, just as in the case of the swing, gravitational potential energy is converted to potential energy as the swing descends.



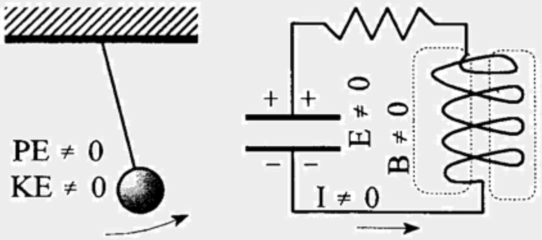
Time = 1/8 T

The capacitor is *fully* discharged, and all of the energy is in the inductor's magnetic field. Just as the speed of the pendulum will be greatest at the bottom of its swing, the current flow will be greatest at this point.



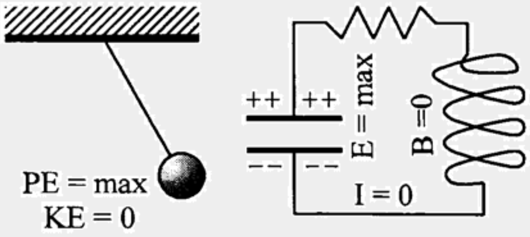
Time = 1/4 T

The magnetic field in the inductor begins to collapse, and the energy that was in the magnetic field provides the voltage or *emf* to drive the current. This current starts to charge the capacitor.



Time = 3/8 T

This completes a half cycle for either the pendulum or the LRC circuit. The magnetic field has dropped to zero, but the capacitor is *fully* charged and all the energy is now stored in the capacitor's electric field. During the second half of the cycle, for the pendulum, the mass will move in the opposite direction, and in the LRC circuit, the current will flow in the oppose direction Note that the direction of the electric field in the capacitor reverses in the cycle at times 1/4 T and 3/4 T while the magnetic field reverses at times 0, 1/2 T, and T.



Time = ½ T

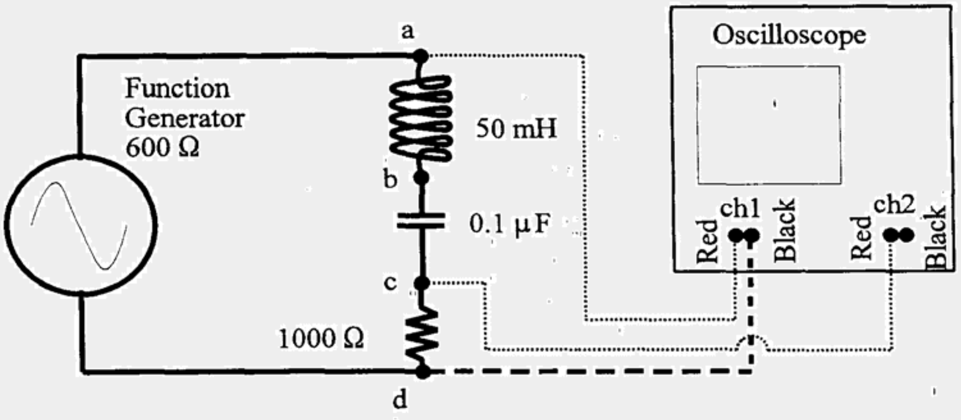


Figure 2 The circuit for measuring the current in an LRC circuit as a function of frequency. The values of the components may vary. Because the input resistance of the scope is much larger than the other parts of the circuit, it has basically no effect on the functioning of the circuit.
Be careful with grounds of the scope and function generator.

Great, there is current flowing through the earphone at about a million cycles per second, but we cannot hear that, so, where's the music? (Note we have both the frequency of the radio which is at about a million hertz and the frequency of the sound at about a thousand hertz to consider.) The radio station changes the peak strengths (amplitudes) of the electric and magnet fields in the radio waves it produces to match the music (Amplitude Modulation). This means that the peak current in the antenna system varies at the frequency of the sound of the music and thus the amplitude of the signal in the LRC circuit varies with the frequency associated with the music. The diode and the relatively slow response of the earphone filter out the high frequency of the radio wave, leaving only the audio frequencies of the music.

This experiment deals with understanding the resonance of an LRC circuit which is the heart of the crystal radio. Resonance in an LRC circuit occurs when the capacitive reactance, X_C, equals the inductive reactance, X_L. At this point, when these two reactance are added together vectorially, they exactly cancel each other because they act 180^o out of phase from each other (see the theory section of the next experiment for full details). Recall: the voltage drop ΔV across an element is related to the current I by $\Delta V = I X$,

$$X_C = 1/(\omega C) \quad \text{and} \quad X_L = \omega L$$

Thus if the condition for resonance is that the two reactance be equal the resonant frequency will be:

$$\omega^2 = 1/(LC)$$

e1. For a 50 mH inductor and a 0.1μF capacitor in an LRC circuit, calculate the resonant frequency.

e2. What is the relationship between the angular frequency, , that is measured in radians per second, and the frequency, f, that is measured in cycles per second? What is the relationship between angular frequency, ω and the period, T, of a sinusoidal oscillation, i.e., time it takes to complete one cycle?

WHAT EXPERIMENT SHALL WE DO?

The general procedure is connect a sine wave oscillator in an LRC loop, see fig. 2. In the frequency range near resonance, use an oscilloscope to measure the current flow in the circuit as a function of the frequency. For the same capacitor and inductor make measurements for two different resistors, and for the same resistor and inductor make measurements for two capacitors. For one inductor-resistor-capacitor set, also observe the phase of the current relative to the phase of the driving oscillator, and the voltages across the inductor and capacitor.

We need to connect the resistor, the capacitor, the inductor and the function generator as shown in fig. 2. The oscilloscope will be used as a monitor of the driven LRC circuit.

- Rl=1000Ω, R2=5000 Ω,and
  Cl =0.1 μF C2=0.01 μF

HOW SHALL WE DO THE EXPERIMENT?

Resonant frequency

For the pairs C1,Rl; C l, R2, AND C2, R2:
With your combination of inductance, L and capacitance, C, calculate the resonance frequency, ω_{res}.
Set the function generator to produce a sine wave at this calculated resonant frequency ω_{res} and set the TIME/DIV on the oscilloscope to about setting equal to about one half the period of this sine wave.
To find the actual resonant frequency, use the same basic method you use to tune a radio. That is find the strongest signal. By changing the frequency of the signal produced by the function generator maximize the amplitude of the current through the resistor which can be monitored on the oscilloscope.
Use the oscilloscope to measure the actual period, T_a, at resonance and calculate the actual resonant angular frequency, ω_a. It is important to have the variable time/div set to the calibrated position while making this measurement. What could account for any difference between the calculated resonant frequency ω_{res} and the measured resonant angular frequency, ω_a?

Current as a function of the driving frequency.

The next step is to measure the amplitude of current, I, through the circuit as a function of the driving frequency ω, of the function generator, and to observe the phase difference, Φ , (see equipment notes) between this current flow and the driving voltage provided by the function generator. Do this for a range of frequencies from about $0.2\omega_{res}$ to $5.0\omega_{res}$. Plot $I(\omega)$ vs ω . Take enough data to see where things change quickly for either I or Φ.

e3. What is the general effect of reducing resistance in an LRC circuit on the behavior of the circuit at resonance and the resonant frequency.
e4. What is the general effect of reducing capacitance in an LRC circuit on the behavior of the circuit at resonance and the resonant frequency?

Devising high- and low-frequency filters.

The final part of this laboratory is to use L, R and C elements in a circuit of your design such that only input voltages at frequencies above a given frequency will end up in the output terminals, or only input voltages below a given frequency will be transmitted. In other words, arrange the L, R, and C such that when you connect the function generator to the input terminals and your oscilloscope to the output terminals, you will see signal only for frequencies significantly above some frequency:

+●------- your ---●
input circuit output
-●------- here ---●

You will want to whiteboard your designs and have a class discussion. Perhaps the work can be shared.
How sharp is the cutoff? What affects that cutoff? Can you use reactance and current ideas to explain how this works?

EQUIPMENT:

Resistor board (10 Ω to 22 kΩ)
Capacitor (0.005 to 0.47 μF) & Inductor (2.5-100 mH) board
DMM (Volts AC/DC input impedance 10 MΩ except 100M on 400mV)
Oscilloscope (1 M Ω input impedance)
Function generator
In room: Lead wires
Crystal radio demo
BIG LRC Demo

Equipment notes:
To make phase measurements it is often useful to expand the horizontal scale using the VARIABLE TIME! DIV knob in such a way that the one complete cycle is four division wide on the screen. Then one division will equal T/4 = 90° = Tt/2 radians. One can use the horizontal position to align the portion of the cycle with the ruling on the screen.
Each channel of the oscilloscope and the function generator has a ground connection. These ground connections are basically connected together by the AC power line. Be careful not to short out the circuit by connecting the ground to more than one point in the circuit. Use the 2-to-3 prong adapter on the function generator.