Lab 1. Resonance and Wireless Energy Transfer

Physics Enhancement Programme
Department of Physics, Hong Kong Baptist University

1. OBJECTIVES

- Introduction to the concept of resonance
- Observing resonance through LC tank circuit
- Wireless magnetic energy transfer

2. INTRODUCTION

Resonance is a ubiquitous phenomenon in nature. It refers to the tendency of a system to oscillate at a large amplitude at a particular frequency. The special frequency is known as resonant frequency. Away from the resonant frequency, the amplitudes of oscillations become progressively smaller. One of most striking examples of resonance is the destruction of a wine glass by a musical pitch tuned at its resonant frequency. Optical resonance in an optical cavity gives rise to laser. In this lab, we will explore the magnetic resonance, and apply this concept in wireless energy transmission.

Several wireless energy transfer methods are conceivable. First, there is the well-established method of radio-frequency (RF) broadcast method. Energy is transferred to distant objects by electromagnetic waves. Radio stations rely on this method to transmit RF signals to the receivers. However, in this process, the received power levels by radios are many orders of magnitude smaller than the transmitter. Thus all radios need amplifiers (powered locally or by batteries). Another method is inductive coupling. This method only operates at short distances of about a centimeter. Applications include, e.g., induction cookers in household kitchens, rechargeable toothbrushes, and in some cell phones. In this lab, we will adopt a technique that has captured growing attention. It works on the principle of magnetic resonance between two nearby induction coils. It was reported that efficient energy transfer of 50% can be transmitted from the transmitter coil to the receiver coil over a distance of 2m [1]. The rest of the manual looks into resonance using an inductor (L) and a capacitor (C). The second part applies this simple concept for constructing a receiver for wireless magnetic energy transfer.

3. BASIC THEORY

An inductor is an electrical conductor that can store energy in a magnetic field. A simple inductor can be made by taking a conducting wire and wrapping it around a cylindrical object to form a coil. When a current *i* goes through the coil, a magnetic field B will be produced. The magnetic field B can act on permanent magnets or magnetic objects such as iron nails. The magnetic energy stored (U_B) in the coil is related to the current i by:

$$U_B = \frac{1}{2} L i^2 \qquad (1)$$

Here, *L* is the inductance of the coil, and its value is related in details to the geometry, and the dimensions of the wire that form the coil.

Analogously, a capacitor is an object that can store energy in an electric field. A capacitor can be formed by putting two conductors (usu. two metal plates in parallel) in proximity. When the positive and negative terminals of a battery (voltage output V) are connected to the capacitor, the capacitor will be charged up to an ultimate potential difference of V. In between the plates of the capacitor is an electric field E that can act on charges. The electric energy stored (U_E) in the capacitor is related to V by:

$$U_E = \frac{1}{2}CV^2 \qquad 2$$

An inductor and a capacitor can be connected in parallel. Such a circuit forms a resonant circuit (also known as a "tank circuit"). Imagine a tank circuit has a switch as shown in Fig. 1. The capacitor can be connected to L or to a battery. When it is connected to the battery, the capacitor will be charged up to V. The total energy is stored in the electric field of the capacitor. When the switch is thrown to the connection to the inductor, the capacitor will gradually discharge. Its voltage will be reduced gradually, and so will be U_E. Simultaneously, the current *i* through *L* will increase gradually, and so will be U_B. When the capacitor is completely discharged, v = 0. At this moment, *i* is the largest. All the energy of the system is now magnetic. However, the current will continue to flow. As it does, the capacitor will be eventually charged up to v = V, but with the opposite polarity. At this moment, v is the largest. All the energy of the system is now completely electric. We now clearly have an oscillator.

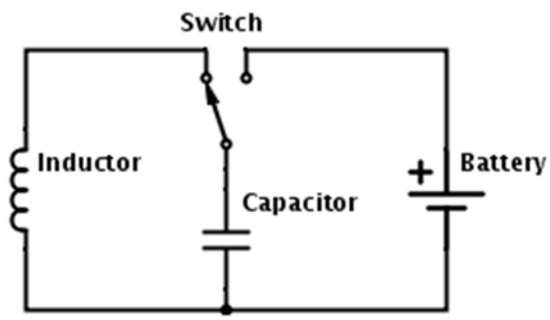


Fig.1 Tank circuit

To derive the frequency of the oscillator, we observe that, in the absence of any loss, the total energy of the system U is conserved. So we have,

$$\mathrm{U} = U_E + U_B = \frac{1}{2}Cv^2 + \frac{1}{2}Li^2 \qquad 3$$

Differentiating both sides by t, and setting the left hand side to 0, we get

$$0 = \mathrm{Cv}\frac{dv}{dt} + Li\frac{di}{dt} = vi + Li\frac{di}{dt} \qquad 4$$

$$v + L\frac{di}{dt} = 0 \qquad 5$$

Since *v = q/C* and *i = dq/dt*, we found

$$\frac{d^2q}{dt^2} = -\frac{q}{LC} \qquad 6$$

This is a differential equation with a periodic solution *q*(*t*) in time. The period of the oscillations is *T*, and is related to the frequency *f* by

$$\frac{1}{T} = \mathrm{f} = \frac{1}{2\pi\sqrt{LC}} \quad 7$$

f is the resonant frequency of the tank circuit. In real life, a tank circuit is commonly used as the detector circuit in a radio receiver. In such a case, *C* is a tunable capacitor whose value can be altered. In this way, channel selection can be achieved as the tank circuit comes into resonance with different radio channels.

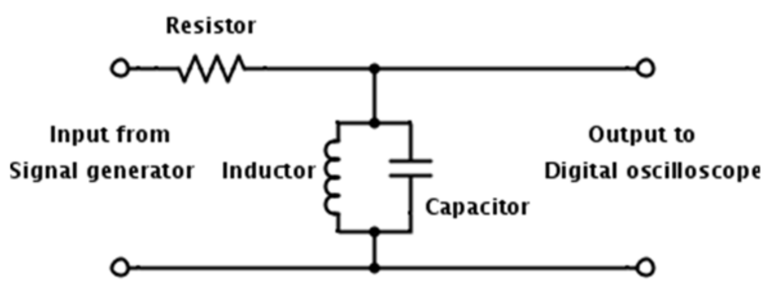
4. EXPERIMENTAL DETAILS

Apparatus:

- Signal generator
- Oscilloscope
- Transmitter coil
- Printed circuit board
- Set of capacitors
- Bundle of wires for making the receiver coil

A. Observing and characterizing resonance LC circuit

Obtain a printed circuit board as indicated from your instructor. Onto the circuit board, you can insert different combination of *L* and *C* to form a tank circuit. A resistor *R* (= 120 Ω) is added intentionally, and in series to the tank circuit as indicated in Fig. 2. The overall circuit diagram is shown below.



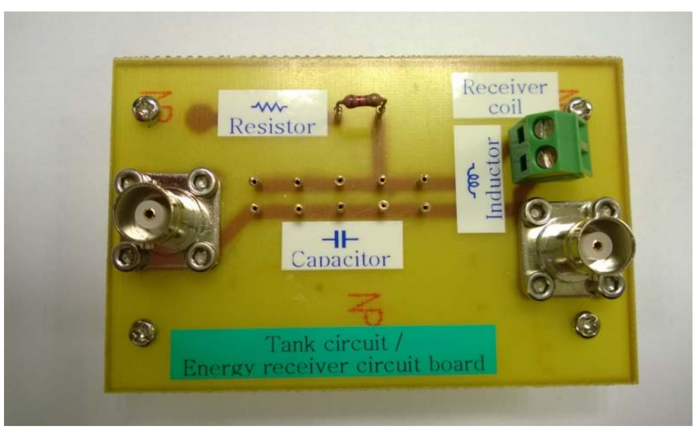


Fig. 2 Tank circuit / Energy receiver circuit board

Start by using L = 0.1 mH and, C = 1 nF. Compute the resonant frequency. Now you need to do the observation. Drive the tank circuit with sine waves using a signal generator. Observe both the input sine waves and the output of the tank circuit with a digital oscilloscope. To start, select for the input sine wave a peak-to-peak voltage of 2 V (keep it fixed for the rest of this part), and choose f = 100 Hz. Write down the peak-to-peak voltage of the output. Complete the table below.

f (Hz)	V_{out} (peak-to-peak)	V_{out} / V_{in}
100		
1k		
…		
2M		

Some suggested values are f = 100, 1k, 100k, 200k, 500k, 800k, 1M, 1.5 M, 2M Hz.

Plot V_{out} / V_{in} vs f. You should see a well-defined peak. Does the position of the peak match your expectation? Next, determine the two points f_1 and f_2 at which $(V_{out}/ V_{in})^2 = 1/2$. At these two points, the energy stored in the tank circuit is 1/2 of the maximum possible value. The bandwidth (BW) of the resonant circuit is defined by the difference between f_1 and f_2. What is the BW of your circuit?

B. Constructing an inductor for wireless energy transfer

In this part, you need to assemble a coil and measure its inductance. First obtain around 3 m of wires (Gauge # 18AWG) from your instructor. Wrap the wire around your fingers of your left or right hand. About 10 turns will form a respectable coil for the later part of your experiment. Use cable ties to secure the coil so that its diameter is between 8-12 cm. Remove the insulating shields at both ends of the coil. Now, you have an inductor.

To measure its inductance L, secure both terminals of your coil to the circuit board as indicated in Fig. 2. Connect a 1 nF capacitor (C) in parallel with L. Then use the signal generator to provide a 2V peak-to-peak waveform to the input of the new tank circuit. Sweep the frequency of the input until you observe the resonant frequency. Repeat the experiment with different values of C and note the resonant frequencies. Fill in the table below.

C (nF)	f_{res} (Hz)
1	
2	
3.3	
10	

Make a suitable plot and determine the inductance of your coil. What is the theoretical inductance? Estimate the percentage error in your experimental measured inductance.

C. Wireless energy transfer using your inductor as the receiver

In this part, you need to use the coil constructed in last part as the energy receiver. First obtain the energy transmitter circuit board from your instructor as indicated Fig. 3. The transmitter is a transistor electronic oscillator that can put out electromagnetic energy with a frequency f. For our oscillator, f typically is between 0.5 to 3 MHz. To get the oscillator running, first connect the transmitter coil to the circuit board. Then you need to connect the transmitter to the source of energy. In this case, it is a set of AA dc batteries connected in series. Find out how many are there and write down the dc voltage needed to drive the oscillator. When everything is ready, turn on the power switch. Observe with the oscilloscope the waveform at the output (have your instructor show you where to make the connections). What is the frequency f of the transmitter?

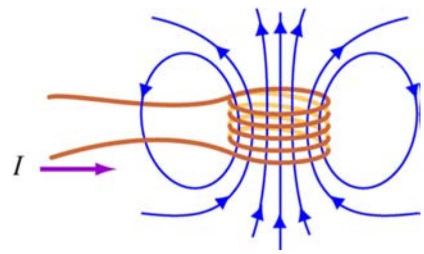
Fig. 3 Energy transmitter circuit board

According to electromagnetic theory, an alternating current in the coil produces an alternating magnetic field around the coil. In short, the coil in the transmitter behaves as a magnet. If you look at the coil face-on, its polarity will change from N-pole to S-pole and then back to N-pole in $1/f$ seconds. When a second (receiver) coil is placed in the proximity of the transmitter coil, the alternating magnetic field from the transmitter coil will induce, according to Lenz's Law, a voltage across the receiver coil. In this way, energy can be transmitted from the transmitter coil to the receiver coil. A transformer works in this manner. But the two coils need to be very close (separation much smaller that the sizes of the coil).

To transmit energy over a distance equal to or more than the dimension of the coils, we use the concept of resonance. When two systems have the same resonance frequency, energy can be exchanged efficiently between the two systems with little energy loss. To see if this concept is indeed useful, connect a capacitor C in parallel with L from Part (B) to form a tank circuit. You need to estimate the value of C using Eq.(7). In addition, connect an LED across the tank receiver coil. Now, place the transmitter coil flat on the lab bench. Then move the receiver coil around until you see the LED glow brightly. Choose the most favorable positions and orientations for the receiver. Then take 2-3 pictures with your cell phone. Attach these pictures to your report. Vary C, and see if the brightness of the LED can be optimized.

Suggested data analysis

1. What is the optimized value of C? Does the value agree with your expectation?
2. Place the receiver coil flat on the lab bench, and side-by-side with the transmitter coil. Use an oscilloscope to observe the output wave form. What is the frequency and amplitude of the output sine wave as seen in the receiver? Is the frequency the same as the transmitter?
3. The following diagram shows the magnetic field lines around a coil:



   Think of the coil above as the transmitter coil. At some positions/orientations, when the receiver coil is near the transmitter coil, the magnetic field can be quite strong and yet no magnetic energy can be transferred to the receiver. Mark on the diagram such positions, and explain why no energy transfer can be observed. Use some pictures to support your answer.
4. How far can you move the receiver coil before the LED goes out?
5. With the LED on, insert different objects between the transmitter and the receiver. See how the output is affected (if any).
6. Suggest some potential applications of this technology. Discuss the potential danger(s), if any.

References:

[1] "Wireless Power Transfer via Strongly Coupled Magnetic Resonances" André Kurs et al., Science 317, 83 (2007).

mhchan, Revised Version: February 2015
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