Sugar Capacity

A Practical Introduction to AC Theory

This version of the problem has been adapted to be an experimental introduction to AC Theory.

Intended Learning Outcomes

By the end of this activity students should be able to solve problems involving:
- Capacitance (and their effect in series and parallel)
- LCR circuits
- Inductance in a solenoid
- Dielectrics
- Parallel Plate Capacitors

Students will use the following skills:
- Designing of experiments to test a hypothesis
- Evaluating the errors in an experiment and their consequences
- Working as a team
- Report writing

KEYWORDS:

   AC circuits, Capacitance, dielectric, electric current, electricity, experimental, inductance, LCR circuits, parallel plate capacitor, Q-factor, resistance, solenoid

Contents

'Sugar Capacity' is run as a Laboratory Group Research Project for students on the Physics degree at the University of Leicester. It is undertaken by students in small groups (of approximately 4 first year students) working as teams to perform a variety of experiments to answer a set of questions posed to them. There are four laboratory sessions of 3 hours each as well as two facilitated workshops. For each of the workshops there is set question for class discussion, that are marked at the workshops. These workshop questions are designed to support the practical work by providing ideas and relevant theory. Most of the required theory can be found in any undergraduate physics text book.

The original version can be found at http://open.jorum.ac.uk/xmlui/handle/123456789/3335

Reading List

The following textbooks are suggestions, other equivalent textbooks are available:

- Breithaupt, J. *Physics.* Palgrave Foundations.
- Tipler, P.A. *Physics for Scientists and Engineers*. Freeman.

Problem Statement

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Extracted from *Chocolate* by Michael Freemantle

WHAT'S THAT STUFF?

Can you imagine chocolate without science? Probably yes. Well, think again the next time you snap a bar of that delicious stuff. Although the preparation of top quality chocolate products may be regarded as an art form, modern processes for manufacturing the most popular brands rely heavily on science and technology.

The essential ingredient in all chocolate is cocoa beans. After harvesting, the beans are fermented in order to develop the chemical precursors of the chocolate flavour, then dried and transported to chocolate factories. At the factory, the beans are roasted and broken up into pieces called nibs. The nibs are then ground into chocolate liquor – a thick brown liquid that solidifies at about room temperature.

During processing, chocolate spends much of its time as a liquid. Viscosity, flow properties, and particle size are therefore important factors in chocolate manufacture. The next stage in chocolate manufacture involves cooling the liquid under controlled conditions to allow the fat, which holds all the solid sugar and cocoa particles together, to set in a crystalline form that has a smooth texture and appealing appearance.

From the documentation it is clear that the control of the size of sugar particles is important in chocolate manufacture. The Granada Chocolate Company is a small company in the Caribbean which might benefit from semi-automating the grinding process. To do this is it would be necessary to check the granularity of the sugar being introduced to the mix. It has been suggested by your research department that a simple way to check the granule size is to measure the bulk dielectric constant of the granulated sugar using an LCR circuit.

Your task is therefore to investigate if the granularity of sugar can be checked by determining its dielectric constant.

Suggested Deliverables

Individual or group reports to the director of research.

Laboratory Equipment Provided

Throughout the stages of this experiment students will require a:
- Pair of induction coils (one wider than the other)
- Computer-based signal generator (or) modular signal generator box and Variable Signal generator.
- Computer-based oscilloscope
- Fixed value capacitor
- Circuit bread-board
- Speaker/ Audio amplifier
- Variable capacitor (consisting of a Perspex strip and two lengths of sheet metal)
- Parallel plate capacitor which can house sugar
- Quantity of sugar
- Pair of small plastic clamps

Students should have access to:
- Wayne Kerr Component meter
- Length of wire to use for connections
- A selection of resistors
- A micrometer of Vernier-Calliper

Laboratory Sessions

The following questions have been grouped in a way that should roughly correspond to four laboratory sessions. It is expected that groups will have researched the relevant theory before they arrive in the lab, and will perform some analysis of results after the laboratory sessions.

Session 1

Session Aims

In this session you are asked to research, understand and build an LCR circuit.

1) Measure the self-inductance of a coil, L
2) Compare with a calculated theoretical value
3) Find a formula for the resonant frequency of an LCR circuit
4) Build an LCR circuit, and note the values of components used
5) Find and evaluate the Q (quality) factor
6) Sweep through the frequency range of the input, and record the output voltage
7) Plot the results
8) Repeat the above steps (6 and 7) using a different resistor value
9) Compare your experimental results to the theoretical values

Suggested Experimental Method

It should be possible to measure the inductance of the coils you have by using the Component Meter, which you should have access to. (See the 'How to use Equipment' Section in 'Supplementary Information').

Once the circuit is set up, you can sweep through a range of frequencies of the driving voltage and measure the output for each. Plotting the results should let you see a resonance peak. Doing this for all possible input frequencies would however take a long time, as the peak may be very small. What would you need to know to estimate the position of the peak before beginning the experiment, thus reducing the range you have to 'sweep' over?

Note: Contrary to what you may expect, we do not put the capacitor, inductor and (if used) resistor all in series with the signal generator. A signal generator is designed to drive a circuit at a set amplitude independently of the resonance condition. Therefore, we isolate the signal generator from the circuit by coupling it through induction coils. (See 'Induction Coils' section in 'Supplementary Information').

Session 2

Session aims

In this session you are asked to investigate the effect capacitance has on an LCR circuit. Once you have an understanding of this, you are to use the resonant frequency of the circuit and a signal generator to measure the capacitance of a parallel plate capacitor given to you.

If the relationship between capacitance and resonant frequency is fully understood, you can use the same process of measuring to investigate the dielectric properties of a sheet of Perspex.

Suggested Experimental Method

You will use largely the same methods as you used in the previous lab session, as you still have to drive the LCR circuit at a range of frequencies in order to find the resonant frequency.

You need to consider how the capacitance of the parallel plate capacitor can be modified using the dielectric, and how to relate any changes you make to the dielectric constant of the Perspex.

Session 3

Session aims

Once you have a working LCR circuit, it should be possible to substitute the sugar container for the previously used parallel plate capacitor, and start using sugar as the dielectric. In this way the dielectric constant of sugar can be found.

Suggested Experimental Method

It is possible to approximate the capacitance by measuring the dimensions of the capacitor. However, unless a micrometer is used, the result will not be very accurate. It can, however, be used to give you a good idea of what range to sweep the frequency over.

Then sugar can be added placed inside the capacitor, and the change in the capacitance measured.

Session 4

Session aims

We now aim to bring together all of the theory and developments made so far. We want to apply them to the originally mentioned scenario: can we make a circuit which gives off an alarm when the sugar content or granularity changes to specified value?

You should aim to design a warning system and explain how it should work. If time permits, you can build the system with the equipment you have, and test whether or not it works.

Suggested Experimental Method

The construction of the circuit may be very similar to those previously used.

You have to consider the width of the resonance peak you want (and how to achieve this), as well as how you intend to create a signal when the sugar reaches a specified level.

Hint: Some waveforms have been written for you in the signal generator library. Examine their form and consider how they may be useful.

Supplementary Information

Computer Software

Set-up:

1) Start/ Programs/ Pc-lab2000se/ Pc_Lab2000Se
2) Turn on all devices at the plugs
3) Check USB devices present. You will need:
   LPT device: PCS500 (PC scope) (drop down box set to the correct port (378 on mine, although this may change. Error message if wrong)
   USB Device: PSCU1000 (Function Generator)
4) Press OK.

The main window should now be displayed, showing an oscilloscope screen (with nothing on it yet), time divide buttons on the right hand side, voltage divides along the bottom for each channel, and a few buttons (such as Oscilloscope, Spectrum Analyser, Transient response and Function generator) along the top.

5) Click on the 'Function Generator' button. A new window should open.

Function Generator:

Here you can select the form, frequency and output of the signal generated. The form is displayed in the right-hand side box. Exactly what is in this box may be confusing. If you select one of the three standard forms (Sine, Digital and Sawtooth) it shows two wavelengths in the box. However if a specified other waveform is loaded, then the entire box represents one 'wavelength'.

For an example, click on the sinusoidal pattern at the bottom left. Two wavelengths should be present in the box. This may seem trivial with something such as a sine wave. However, you may want to have a more complicated function, such as a modulated sine wave with a carrier frequency and modulation frequency. In this case, you will need to know that the computer means when it says it's driving the circuit at a given frequency. Knowing that the box shows a single wavelength can help you in this situation.

Preliminary Exercise:

Try connecting both the function generator and oscilloscope to the same points in a circuit (or just connect them together). Set the function generator to a Sine wave at a frequency of 10kHz. Click on 'AUTOSET' in the oscilloscope window just under the main screen. You should be able to see the function generated on the main window (if the 'Oscilloscope' button at the top of the screen has been depressed). Clicking on the 'AUTOSET' button will make the computer decide what voltage and time divide to use. Bear in mind that its choice is often wrong, and that setting it yourself can often be a better idea.

If you want to measure a wavelength, you can select the 'Single' (rather than 'Run') option on the oscilloscope (Right hand side centre) to take a single frame. The wavelength can then be observed.

Try selecting the sawtooth or digital waves. You should see that the forms seen in the oscilloscope window are wrong (if not, excellent. The drivers may have been updated!). Some waveforms are not produced properly by the signal generator at certain frequencies.

For most of your experiment, you should be able to use the sine form. If you want to load a different form (such as a modulated Sine wave) you can click on 'MORE FUNCT.', select 'Library waveforms' and then select the form you wish to use.

Helpful Options:

In the oscilloscope window, under the 'View' tab, you can select the option to see the waveform parameters. In here is the RMS voltage. You may want to be able to quickly compare the output voltage at two different frequencies, so the option to see the RMS output, as well as the fundamental frequency, can be very useful.

How to use equipment

Wayne Kerr Component Meter:

This allows you to measure the resistance, capacitance and inductance of a component, and is therefore very useful when dealing with LCR circuits.

The object to be measured should be connected to both of the 'measure' sockets, and the property to be measured selected using the buttons labelled 'R', 'C' and 'L'.

The range of the meter does not automatically adjust for whatever component is connected. Therefore you must manually alter the knob on the right to select the magnitude. If an incorrect magnitude is selected, a small arrow will flash (either 'up' or 'down') at the right of the display. Adjust the dial in the direction stated, one step at a time, until no arrow is present.

You can then take the reading.

Induction coils:

The signal from some generators will be adjusted so that it has a continuous voltage or wave parameters depending on the components it's connected to. As we are using an LCR circuit, this may interfere with our results. For this reason, we will not directly connect the signal generator to the circuit. Instead, we will place two coils one inside the other and power one, taking readings from the other (like a transformer).
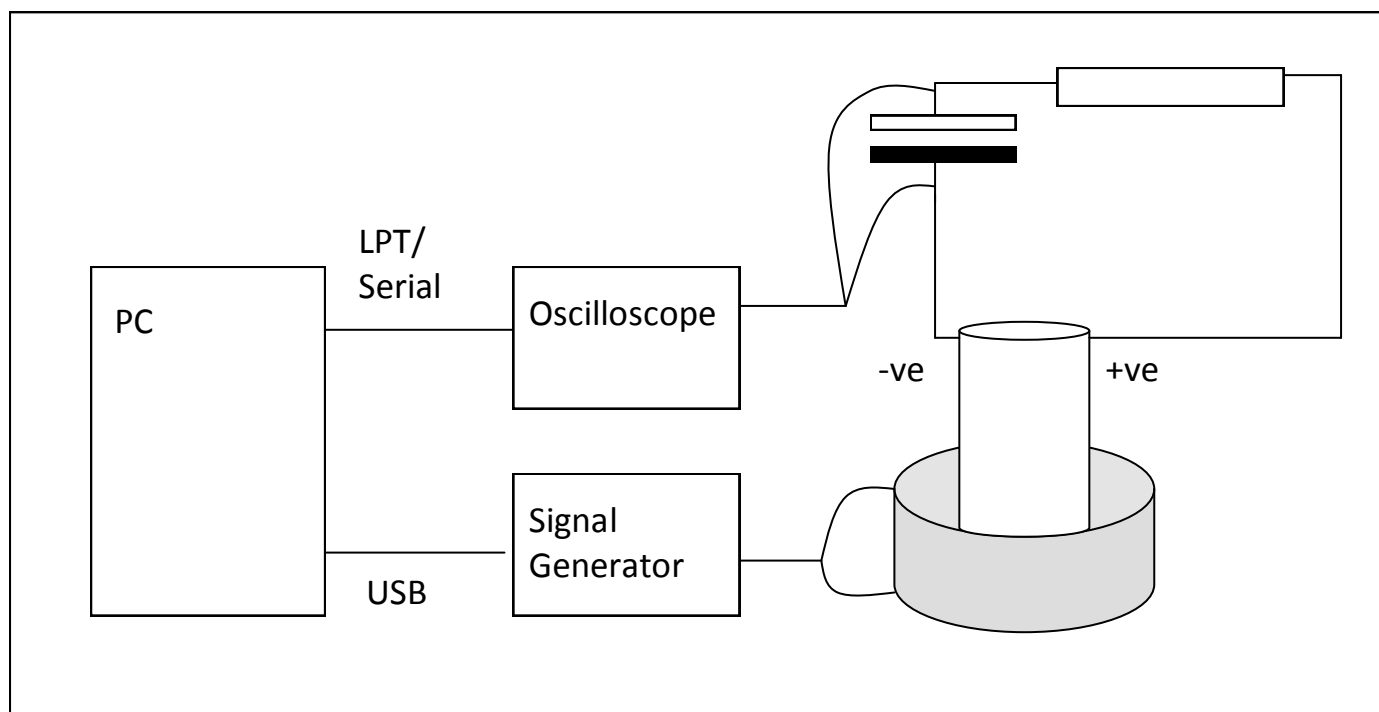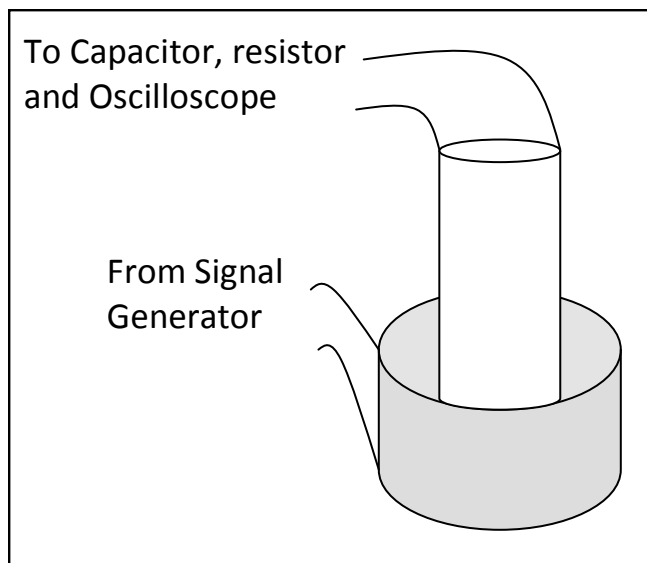
Circuit Connections:

Where:
- 'Oscilloscope' is the Velleman PCS500 PC-Scope
- 'Signal Generator' is the Pc-Function Generator PCSU1000
- These components must be specified to PC-lab in order for them to work. This should be done on the startup screen.

Questions for Class Discussion

1. Derive an approximate formula for the inductance of a coil in terms of its physical dimensions, stating your assumptions. How does the inductance depend on the area of the coil and the number of turns? Explain this dependence in physical terms

2. Derive a formula for the capacitance of a parallel plate capacitor in terms of its physical dimensions. How does the capacitance depend on (a) the dielectric (b) the plate area (c) the plate separation? Explain this dependence in physical terms.

3. What is the resonant frequency ω of (i) an LC series circuit? (ii) an LC parallel circuit. Why do these have the same dependence on L and C?

4. How would you increase the Q-value of a circuit without changing its resonant frequency?

5. How does the rate of power dissipation change as the Q-value is increased for (a) a damped SHO, (b) a forced, damped SHO, (c) your LCR circuit?

6. The width of the resonance curve $\Delta\omega$ at resonant frequency ω_0 in a circuit with quality factor Q is given by which of the following:
   a) ω_0
   b) $Q\omega_0$
   c) ω_0/Q
   How can you explain this result?

7. The differential equation for a driven LCR circuit is

$$L\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{1}{C}Q = V_0\cos\omega t$$

   By analogy with a forced oscillation of a mass on a spring, what are the equivalents of mass, damping and resonant frequency?

8. Two capacitors C_1 and C_2 are in series. What is the overall capacitance? What is the capacitance if instead they are in parallel?

9. The circuit shows a plan to provide an audio signal to warn of changes in the dielectric constant of the sugar granules. What is the role of the rectifier in the circuit?