The experimental part of BK2 – Physics

Fundamental concepts

Charge (ladning):

Charge, Q, is a fundamental property of matter like mass is. Static charges also interact in a way that is analogous to the interaction between masses. However, there is the difference that charge can be either positive or negative, and that charges of opposite sign attract each other while charges of the same sign repell each other. Charge is measured in Coulomb denoted by the letter C.

Current (strøm):

Current, I, is moving charge. In an ordinary wire it is electrons that move. Electrons carry negative charge. Other examples of charged particles are ions and the proton (which you can also think of as a positively charged hydrogen ion). Current is measured in Coulomb per second which is called Ampere and denoted by the letter A.

Voltage drop (spændingsfald):

Voltage drop or voltage difference, U, is what drives the current. It is the potential energy difference between two points per unit charge. Voltage drop is often just called voltage. Voltage is measured in Volt denoted V.

Ohms law and resistance:

Ohms law describes the relation between the voltage over a resistor and the current running through it:

$$U = RI \tag{1}$$

where U and I are the voltage and current described above and R is the resistance. Resistance is a measure for how difficult it is to drive a current through a resistor. Ohms law (eq. 1) shows that there is a proportionality between voltage and current. The larger the resistance is, the more voltage is needed to drive a given current. Resitance is measured in Ohm denoted by Ω (the Greek letter omega in its capital form).

In the case of an oscillating voltage the current will also be oscillating and the voltage and current will follow each other:

$$U_0 cos(\omega t + \phi) = RI_0 cos(\omega t + \phi) \tag{2}$$

where U_0 and I_0 are the voltage and current amplitudes, ω is the angular frequency related to frequency, f, by $\omega = 2\pi f$, t is time and ϕ is a phase angle. It follows that Ohms law also holds as a relation between the amplitudes:

$$U_0 = RI_0 \tag{3}$$

Ohms law is a phenomenological law, in fact it is not really a natural law but rather a model. It describes resistors, but it does not give the general relation between voltage and current. In this course we work with elements that do not obey Ohms law. These are described below.

Capacitor (kapasitor) :

A capacitor consists of two parallel conducting metallic plates. The plates can be charged by connecting them to a voltage source. The plate connected to the positive pole will get a surplus charge $+Q$ and the other a corresponding deficit $-Q$. The voltage drop, U between the plates is proportional to the charge:

$$Q(t) = CU(t) \tag{4}$$

where C is the capacitance measured in Farad denoted F. The more charge on the capacitor, the larger the voltage.

Inductor (Induktor) :

An inductor is formed by a wire wound into a coil. When a current runs through it a magnetic field is created around it. The energy needed to create the magnetic field is supplied from the sources creating the current through the coil. This is seen as a voltage drop across the inductor and it is given by:

$$U(t) = L\frac{dI(t)}{dt} \tag{5}$$

Where L is the inductance which is measure in Henry denoted by H. Equation 5 shows that the voltage is proportional to the rate of change of the current. Therefore, the faster the current changes magnitude the large a voltage is needed to drive the current.

Table with names and units

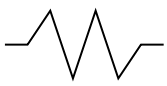
Name	Letter	Unit	Letter of Unit
Charge	Q	Coulomb	C
Current	I	Ampere	A
Voltage	U	Volt	V
Resistance	R	Ohm	Ω
Capacitance	C	Farad	F
Inductance	L	Henry	H

Table with useful metric prefixes

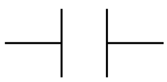
Name	Symbol	Base	Decimal
tera	T	10^{12}	1 000 000 000 000
giga	G	10^{9}	1 000 000 000
mega	M	10^{6}	1 000 000
kilo	k	10^{3}	1 000
		10^{0}	1
milli	m	10^{-3}	0.001
micro	μ	10^{-6}	0.000 001
nano	n	10^{-9}	0.000 000 001
pico	p	10^{-12}	0.000 000 000 001

Illustrations and pictures of electrical components

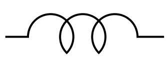
Resistor



Capacitor



Inductor



Experimental Exercises.

Bold red text indicate the questions which must be answered in your report to pass this course. This should be one collected report with both the simulation and experimental part.

The purpose of this part is to gain insight in the use of the function (waveform) generator and the oscilloscope and to learn how to measure a voltage and a current. Furthermore theoretical concepts associated with electrical oscillations will be put in a practical context. A picture of the function generator and the oscilloscope can be seen in figure 1.

Figur 1 A picture of the generator on the left and the oscilloscope on the right.

The Function Generator (in the following called generator)

A function generator delivers an electric voltage $U(t)$, that varies in time t. In particular it can be chosen to vary harmonically at a frequency, f and with an amplitude U_0:

$$U(t) = U_0 \cos(2\pi f t) \tag{6}$$

The frequency and amplitude can be chosen from in at the panel of the function generator.

Make yourself familiar with the function generator by setting different amplitudes and frequencies. You can do this in three different ways:

1 by entering a number (use the button with green text "Enter Number")

2 by turning the knob

3 by using the arrow keys

The Oscilloscope

Answer question 6 and 7 for your report and explain what you did.

The oscilloscope is a measuring device by which one can identify and freeze the temporal development of a voltage. The oscilloscope has a lot of facilities of which we will only mention a few. The keys and knobs are arranged in different fields on the front side as e.g. »Horizontal«, »Vertical« and »Action«.

The cables we use are coaxial cables. Such a cable consists of two independent wires, a central wire surrounded by and isolated from an exterior wire. It is effective at suppressing external electric noise compared to two parallel wires especially when the outer wire is connected to the ground (metal case of devices).

The generator is connected to the oscilloscope in such a way that the output of the generator is measured on chanal 1 (Ch 1). We will refer to the voltage amplitude of this signal as U_1.

4 Set the generator to 1.25 V and 4 kHz.

5 Find and push the button `Autoset` on the oscilloscope. Now the oscilloscope automatically finds an appropriate scaling on the time-axis and the voltage axis.

A picture of the voltage variation is now appearing on the screen. If the vertical scale does not have zero in the center then push the top turning knob in the Vertical region of the oscilloscope (it says "Push to Zero" next to the knob).

Take a picture of the screen for your report.

6 Does the measured amplitude match the amplitude you have chosen on the generator? Explain how you see that.

7 Does this match the frequency you have chosen on the generator? You need to make a little calculation to show this.

8 Try out and describe what happens if you turn the knobs in the »Horizontal«-field.

9 Try out and describe what happens if you turn the knobs in the »Vertical«-field.

10 Now change the frequency of the generator into 20 kHz. Without using `Autoset` you should change the time base in the »Horizontal«-area in order that about two complete oscillation are displayed on the screen. Read off the period.

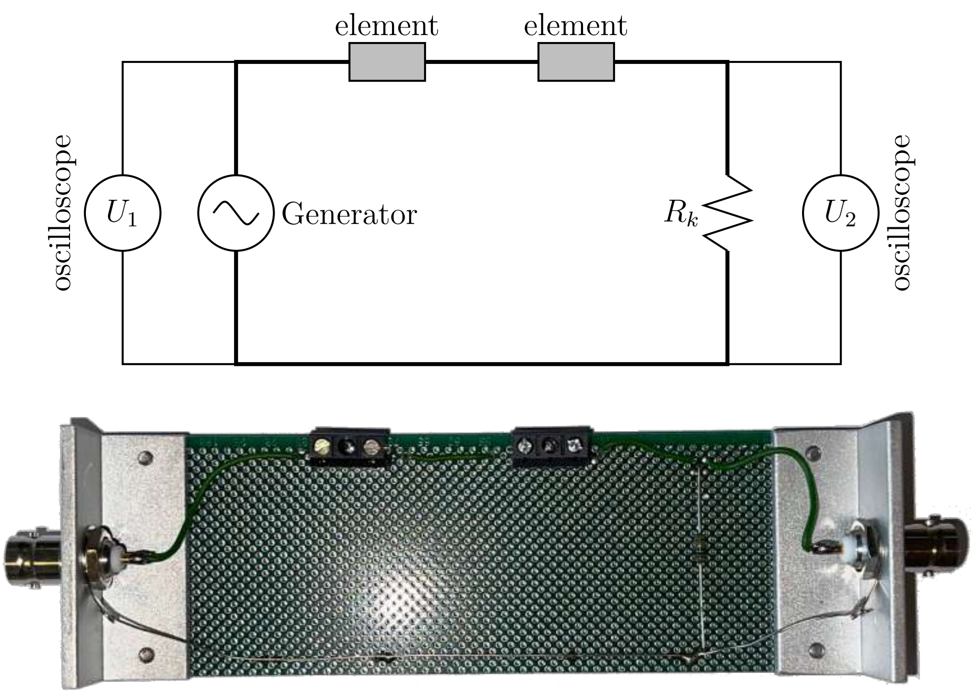
Calculating a current

Answer question 13 and 14 for your report and explain what you did.

The oscilloscope measures voltage but in the following we want to measure both a voltage and a current. To calculate a current we measure the voltage drop over a known resistor and use Ohms law in the following way:

$$U = RI \Leftrightarrow I = \frac{U}{R} \tag{7}$$

We moreover make use of the fact that the current running through two elements in series is the same. By measuring the voltage drop over a known resistor in series with an unknown element we can find the current in the unknown element. You have a circuit board with a 10 Ω resistor we will denote it R_k (subscribt k for known), see figure 2.



Figur 2 An illustration of the electrical circuit and picture of the circuit board. The goal of this figure is to strengthen the connection between the theory and the physical components. The grey "element"boxes on the illustration represent the black boxes on the picture where elements can be added to the circuit in a series connection with the known resistor R_k. However note that U_1 (the oscilloscope) and the generator is not shown on the picture but is instead connected to the left side of the circuit board. Likewise U_2 (the oscilloscope) is not shown on the picture but instead connected to the right side of the circuit board.

11 Connect the unknown resistor, R_u, and the shortcut wire to the circuit board.

12 Connect the circuit board to the frequency generator such that the input voltage is applied to the unknown resistor. Set the voltage on the generator to 10 V.

13 Connect the circuit board to the oscilloscope such that the voltage over the known resistor is measured on chanal 2 (Ch 2). Press `Ch 2`. Measure U_2 and calculate the current running through the known resistor.

$$I = \frac{U_2}{R_k} = \frac{U_2}{10\Omega} \tag{8}$$

Remember that the current is the same in the two resistors because they are in series.

14 Measure U_1 and use the current (I from equation 8) to find the resistance of the unknown resistor (R_u). [1]

$$R_u = \frac{U_1}{I} \tag{9}$$

Oscilloscope Help

- The `Preset` button takes the oscilloscop back to its original state.
- The `Autoset` button finds an adequate scale.
- The `Ch 1` and `Ch 2` buttons decide which of the channels you control on the turning knobs in the vertical area as well as controlling which scale is shown in the y-axis of the screen.
- Pressing the top turning knob in the vertical area centers the y-axis around zero (it says “Push to Zero” next to the knob).
- If a curve is very noisy: Press `Acquire` a panel pops up on the screen. Press “Acquire Mode”, a new menu pops up, press Average, press No. of Averages. Turn the knob in the Analysis section of the oscilloscope to select a higher no. of averages, e.g. 10.
- To get the standard BK2 setting of the oscilloscope do the following. In the Action section of the oscilloscope press `Save Load`. A menu pops up on the screen. Press “Setup” on the menu. Press “Load”. Choose BK2_SETT.SET. Press “Load”. After this you probably need to press `Autoset` and maybe the turning knob with the text “Push to Zero”.

[1] Those who have an interest in physics should be noted that equation 9 is not strictly true, but a good approximation. The correct equation would be $R_u = (U_1 - U_2)/I$. This is because U_1 is the voltage drop over the entire system and not just R_u. The correct voltage drop over R_u, or any two elements connected to the circuit board, is $U_1 - U_2$. However this is a good approximation when U_1 is much greater than U_2. You can calculate R_u with both equations and compare the results to see the size of the error (it should be small).

Determination of the resonance frequency of an oscillating electric circuit.

Answer question 16-18 for your report and explain what you did.

15 Remove the unknown resistor, R_u, and the shortcut wire from the circuit board. Connect the capacitor and the red inductor in series forming an electric oscillator.

16 Vary the frequency and measure the voltage drop, U_1, and the current, $I = U_2/10\Omega$ at least 10 frequencies in the range 2 kHz to 20 kHz. **Report the data in a script as the one shown below and include it in your report**.

17 Plot the quantity I/U_1 as a function of frequency. The frequency where this curve has a maximum is called the resonance frequency.

18 Vary the frequency slowly around the resonance and look at the oscilloscope. What happens to the phase angle?

```
# input
f    = np.array([])      # frequncy              , unit kHz
ppU1 = np.array([])      # peak to peak voltage 1, unit Volt
ppU2 = np.array([])      # peak to peak voltage 2, unit Volt

# calculated quantities
U1   = ppU1/2            # amplitude voltage 1, unit Volt
U2   = ppU2/2            # amplitude voltage 2, unit Volt
I    = U2/10             # amplitude current  , unit Ampere
```

Relation between inductance and resonance time

19 Calculate the period, T_{res}, that corresponds to the resonance frequency.

20 The exercise is repeated with all the different inductors and it is studied how the resonance shifts depend on the self-inductance. Report the data in a script, remember units and think about the number of digits.

```
# input
#                   pink red  glitter black
L     = np.array([2.2 , 4.7 , 21     , 63])# inductance   , unit mH
f_res = np.array([])                       # res frequncy , unit kHz

# calculated quantities
T_res = 1/f_res                            # resonancs time , unit ms
```

21 Plot the period T_{res} as a function of L both in a normal linear plot and a log-log plot. What do you see, and what does it tell you about the relation between T_{res} and L? Both plots should be in your report if you answer this part.

End of the Experimental Exercises.

Theoretical background.

In a simple oscillating mechanical system you can usually recognize two physical objects: a mass and a spring. The mass possesses kinetic energy when it moves and the spring possesses elastic energy when it is stretched. During an oscillation energy alternates between these two kinds of energy. The electromagnetic oscillator is also build by two elements, the capacitor and the inductor.

Capacitor

A capacitor consists of two conducting metallic plates. The plates can be charged by connecting them to a voltage source. The plate connected to the positive pole will get a surplus charge $+Q$ and the other a corresponding deficit $-Q$. The potential difference, U between the plates is proportional to the charge. This holds at any instant, thus

$$Q(t) = CU(t) \tag{10}$$

C is called the capacitance and has the unit Farad. A current I flowing into the capacitor in a little time span dt will increase the charge in the capacitor by $dQ = Idt$. That means:

$$I = \frac{dQ}{dt} \tag{11}$$

Thus if we differentiate (10), we get

$$I(t) = \frac{dQ}{dt} = C\frac{dU}{dt} \tag{12}$$

For a harmonically varying voltage $U(t) = U_0 \cos(\omega t)$ this becomes

$$I(t) = C\frac{d}{dt}U_0 \cos(\omega t) = -\omega C U_0 \sin(\omega t) = \omega C U_0 \cos\left(\omega t - \frac{\pi}{2}\right) \tag{13}$$

By this we can conclude that the amplitudes of the current I_0 and of the voltage U_0 are connected by

$$I_0 = \omega C U_0 \Leftrightarrow \boxed{U_0 = \frac{1}{\omega C} I_0} \tag{14}$$

Equation 13 shows that the current has its maximum a quarter of a period *before* the voltage.

When a capacitor is charged it contains charge of course — but also electrostatic energy. It is much like the elastic energy residing in a stretched spring. If the capacitor is discharged it gives off the energy again.

Inductor

Another electrical component exists, which can store magnetic energy. It is the inductor. An inductor may simply be a piece of an electric wire. When a current runs through it a magnetic field is create around it. The magnetic field can be magnified if the wire is wound into a coil. The magnetic field around such a current-carrying coil looks exactly like the dipolar field of a permanent bar magnet. The energy needed to create the magnetic field is supplied from the sources creating the current through the coil. This is seen as a voltage drop across the inductor that is proportional to the rate of change of the current:

$$U(t) = L\frac{dI(t)}{dt} \tag{15}$$

L is called the self-inductance of the coil and has the unit Henry. The self-inductance expresses a kind of electric inertia since it opposes changes in the current much the same way as the mass of an object in mechanics opposes changing velocity. In mechanics we know this from Newton's 2nd law $F = mdv/dt$, which tells us that the larger the mass the larger a force is needed in order to change velocity. By this analogy the formula (15) corresponds to Newton's 2nd law. The analogy is even deeper since the magnetic energy is $1/2\,LI^2$, which corresponds to the expression of the kinetic energy $1/2\,mv^2$ of a mass m moving at a speed v.

Under the special circumstances that the current alternates harmonically, $I(t) = I_0\cos(\omega t)$, we can calculate the voltage by (15). It becomes

$$U(t) = \omega L I_0 \cos\left(\omega t - \frac{\pi}{2}\right) \tag{16}$$

In the case of an inductor we thus find that the amplitudes of the current, I_0 and of the voltage, U_0 are related by

$$\boxed{U_0 = \omega L I_0} \tag{17}$$

Equation 16 moreover shows that the phase of the current is now shifted one quarter of a period *behind* the voltage.

Oscillating energy

Imagine a mass hanging down from a spring. If you displace the mass from its equilibrium position and let it go it will perform oscillations at a definite frequency, the natural frequency. The energy is oscillating between elastic and kinetic energy. A similar phenomena takes place for an electric circuit consisting of a capacitor and an inductor. Placing a charge on the capacitor gives rise to an electrostatic energy in the capacitor. As an electric current flows from the capacitor and through the inductor the electrostatic energy is converted into magnetic energy. After further a half period the energy returns to the capacitor and the system keeps on oscillating in this way. Electromagnetic oscillators are the basic device for creating electromagnetic waves that are used by all types of wireless radio communication.