Laboratory Exercise 2: Oscilloscope

2.1 Oscilloscope

Oscilloscope is the most usual general-purpose instrument for electrical measurements. It is usually not used for accurate measurements but for estimating waveform-related features (amplitude, frequency, distortion etc.). Oscilloscope visualises the signal under investigation, so it is often necessary to use it as a measurement device.
In most oscilloscope measurements, a picture of voltage (on vertical axis) is displayed as a function of time (horizontal axis). The advantage of an oscilloscope compared to other measurement devices is its versatility. With a single measurement, more information can be gained than using e.g. a counter or a multimeter. With an oscilloscope one can measure from a signal e.g. its DC component, AC component, amount of noise and frequency.
There are several very different types of oscilloscopes, and there are great differences between their performance and properties. Basic functions, however, are the same in all types, and once you know them it is easy to learn how to use any oscilloscope unknown to you beforehand. Familiarity with the operating principle and the possibilities of its usage is a fundamental condition for reliable signal measurements. For this reason this exercise concentrates on understanding the operating principle of an oscilloscope and getting acquainted to its different switches and their use in examination of different signals.

2.1.1 Oscilloscope structure

By its structure, oscilloscope can be divided into four basic subsystems: vertical, horizontal, triggering and display subsystems.

Display

In an oscilloscope the signal is displayed using a cathode ray tube (CRT). In a CRT, an electron beam accelerated by high voltage is generated. When the electron beam hits the phosphor-coated screen it generates visible light at the contact point. The electron beam is deflected from left to right (from the measurer's point of view) at a constant velocity controlled by the horizontal deflection subsystem. Triggering subsystem determines the instant when the signal drawing begins by initiating the horizontal sweep. In vertical direction the beam is controlled by a voltage proportional to the measured signal. Hence the picture of the signal under investigation is drawn on the screen. In many oscilloscopes an external signal can be connected to control the brightness of the beam (Z-AXIS). CRT may have several electron guns, but several signals can be displayed even on a single-gun CRT by coupling them to the vertical deflection plates one by one alternately at very high rate.

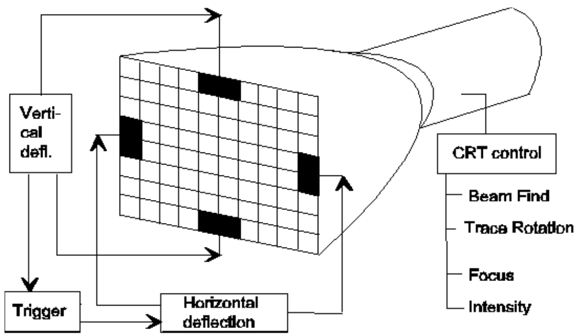


Figure 1.1

Display is adjusted with focus and intensity controls. Some oscilloscopes have a beam finder. It is used for reducing the deflection voltages of the CRT and increasing the beam intensity; thus the direction of the electron beam can be seen and the settings can be adjusted if necessary.

Vertical deflection

Vertical deflection subsystem of an oscilloscope handles the measured signals by controlling the display and the triggering subsystem. In the most usual oscilloscopes the vertical subsystem consists of two channels and an electronic switch that selects the channels and guides their outputs to the output amplifier.
Channel consists of an attenuator and a pre-amplifier. With these the signal amplitude is scaled for the screen and an exact deflection coefficient is formed. Based on it, the screen can be utilised when determining numerical values. Deflection coefficient is usually expressed as volts per screen grid division (**VOLTS/DIV**). Typical numerical values are 1, 2 and 5 on each decade (that is, e.g. 10mV, 20 mV, 50 mV, 0,1 V, 0,2 V, 0,5 V, 1 V etc.).
In most oscilloscopes there is also a possibility for continuous adjustment of the deflection coefficient (**CAL**). Then "absolute" voltages can't be determined from the screen, so during measurements one must always make sure that the CAL control is locked into its calibrated position. For each channel there is a control for adjusting the vertical positions of the signal (POSITION).
Input impedance of the channels is typically 1 MΩ parallel with a 20-pF capacitance. In some high frequency oscilloscopes the input impedance may be 50 Ω. When a channel is **DC** coupled the whole signal is shown on the screen. Channels can also be switched to **AC** coupled mode. Then a serial capacitance is connected to the signal path. It will filter off the DC component and attenuate low frequencies (below 10 Hz). Since the signal displayed on the screen is then zero-mean, it is easier to examine signals with high DC voltage levels. In **GND** mode measured signal is disconnected from the vertical deflection subsystem. Then the level of the ground potential of the oscilloscope (zero level) is displayed on the screen and its position on the screen can be adjusted freely using POSITION control. During measurements, the measurer needs to know where the zero level is.
Vertical deflection subsystem has a switch for selecting the signal to be displayed. Typically there are at least the following options:
Switch in position CH1 or CH2 (A or B); either signal on channel CH1 or CH2 (A or B) is displayed. In some oscilloscopes this is also used for setting the trigger channel. In position DUAL (BOTH) both channels are displayed at the same time.
In alternate mode (ALT) the channel is changed after each sweep and in some oscilloscopes also the trigger signal can be set to always be taken from the current channel. Thus the figure of each channel is swept completely one by one. At high sweep rates the signals can be seen at the same time even though the phenomena are not simultaneous. Thus it is good to use the CHOP mode at least at lower sweep rates and while measuring time differences between signals if one can't be certain that the trigger signal is always taken from the same channel.
In chopped mode (CHOP) the channel connected to display is changed at high frequency (approximately 125 - 500 kHz), and the signal is drawn in small pieces alternating between channels during the sweep. At the instant of switching the beam is turned off, so that both channels seem to be drawn as continuous lines.
In summing mode (ADD) the sum of signals on channels CH1 and CH2 is displayed. Difference between them can be displayed by inverting (INV) one of the signals.
In some oscilloscopes either ALT or CHOP mode is switched on automatically depending on the horizontal deflection rate.
Vertical deflection signal can be taken to the screen through a delay line (about 100 ns), so that the part of the signal that causes triggering can be seen on the screen.

Horizontal deflection

Horizontal deflection subsystem consists of a sweep generator and an amplifier. Trigger subsystem initiates the sweep generator to generate a single sawtooth wave. It is amplified and connected to the horizontal deflection plates of the CRT, and the beam sweeps at a constant velocity across the screen from left to right. The beam is turned off for the time of retrace.
The rise velocity of the control wave is controlled by a switch (TIME/DIV). The deflection amplifier usually has a control that multiplies the amplification by 10 (Sweep magnification). With this

control the sweeping rate can be increased to tenfold, which causes the signal to widen in horizontal direction. Also the horizontal deflection has a position control (X POS) with which the signal can be moved in horizontal direction.
Sweep circuit can often be bypassed (EXT X DEFL, XY). Then the horizontal deflection can be controlled directly by an external signal similarly to the vertical deflection.

Trigger subsystem

Trigger subsystem sets the moment when the oscilloscope starts drawing the signal. Since the measured signal is usually continuous and periodic, it is the trigger's duty to make the drawing start at exactly the same point of the period at every sweep. Trigger subsystem synchronises the horizontal deflection subsystem of the oscilloscope with the measured signal in order to make the display stable. Trigger circuit is fed with a signal that is compared with accurately adjustable DC voltage. When the selected edge of the signal (SLOPE) passes the selected triggering voltage level (LEVEL) an impulse is generated and connected to the horizontal deflection subsystem in order to initiate the sweep.
The different triggering methods are automatic, normal and single sweep.
In automatic triggering (AUTO), a triggering impulse is generated if during a predetermined time (ca. 10-20 ms) after the previous triggering a signal meeting the triggering conditions has not been found. With automatic triggering horizontal deflection will always happen, so there will always be some kind of signal on the display to help making some extra adjustments. In automatic trigger mode, the trigger level control (LEVEL) is often connected to a peak value detector, which is used to force the adjustable area between the signal peaks.

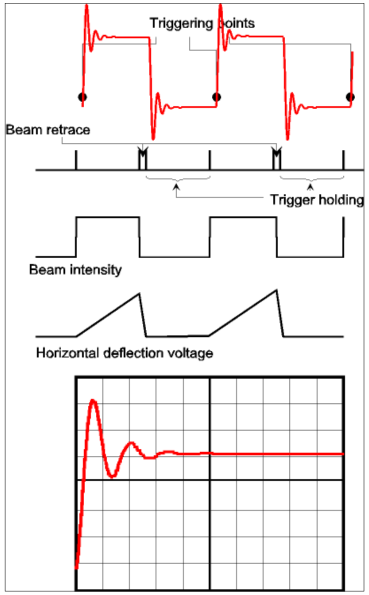


Figure 1.2

In normal triggering mode (NORM) triggering takes place only when a signal level passes the trigger level in wanted direction. Triggering to either rising or falling slope is selected with a separate switch (SLOPE +/-). When trigger level is outside the signal level, triggering won't take place and nothing is drawn on the screen. The triggering signal can be either AC or DC coupled. As AC coupled it has its DC component filtered out.
In single sweep mode (SINGLE) signal is swept only once. This property is very useful in studying non-repetitive events (e.g. coupling of operating voltages). In storage oscilloscope the signal remains on the screen where it can be examined. With an ordinary oscilloscope there is no time to examine a single sweep before it fades out. In this case the signal must be photographed.
Triggering signal does not have to be the measured signal. Usually the oscilloscopes have a connector for an external trigger signal (EXT). Triggering can also be carried out according to line voltage (LINE). Also the sum or difference signals of the channels can be used for triggering. In order to make signals of different frequencies (not multiples of each other) to be displayed steadily at the same time one must use alternating mode and composed sweep (COMP). Then the trigger circuit is first connected to the signal on one channel, and when the trigger level is reached, this signal is drawn on display. After this the other channel is connected to the trigger circuit and when the trigger level is reached again, this signal is displayed.
Some oscilloscopes have adjustable after-sweep trigger holding time (HOLD OFF). During this time signal meeting the triggering conditions will not cause new triggering. This is useful when the waveform under study is complicated and triggering can happen in many positions of a signal period, which makes the display unstable.
The signal may be low-pass or high-pass filtered before triggering. In many oscilloscopes the trigger circuit has a filter, which recognises synchronising impulses of a video signal (TV). New digital oscilloscopes have very versatile possibilities for setting the triggering conditions.

2.1.2 Digital storage oscilloscope

In a digital oscilloscope, the measured signal is pre-processed (signal level is adjusted suitably etc.), A/D converted and stored in semiconductor memory. In addition to the signal itself, information on how much it has been amplified/attenuated is stored. Contents of the memory are then D/A converted and the result is used for the control of the electron beam. Voltages corresponding to the quantized values can be presented as such or they can be joined together with lines or arcs. The number of bits in A/D and D/A converters affects both the resolution and the speed of the oscilloscope.

Comparison of analog and digital oscilloscopes
In an analog oscilloscope, the true signal is displayed completely on the screen. Every part of the signal is shown on the screen. In digital oscilloscope, however, there is a dead time between samples, and no change taking place during this dead time can be seen in digitised signal. The figure is created based on digitised recording with resolution dependent on the number of bits. Analog oscilloscopes have, in theory, infinite horizontal resolution, which leads to a wider measurement bandwidth. In digital oscilloscopes the bandwidth depends on the sampling frequency. In order to prevent the signal from aliasing the sampling rate of the oscilloscope must be at least twice the highest frequency component in the measured signal. The advantage of a digital oscilloscope is easy measurement of single phenomena by signal recording, which makes it possible e.g. to post-process the signal. In addition to this, many digital oscilloscopes are bus controllable and have many built-in automatic functions.

2.1.3 Measurement wires

Oscilloscope is connected to the examined circuit with a **probe**. Probe wire is usually a coaxial cable. The structure of this cable prevents any significant external electromagnetic disturbances from interfering the signal circuit. Using measurement wires causes, however, loading on the circuit, which will change the measured signals. The loading of the measured circuit is both resistive, capacitive and inductive. With signals of frequencies below 5 kHz, resistance is the most significant component. With high-frequency signals, inductance and capacitance become significant. Increase of capacitance is unavoidable when constructing the connections for measurement, but the capacitance can be made as small as possible by using an attenuating probe. The problem with a direct probe is the delay caused by the cable and loading caused by the capacitance, especially in high frequency measurements.

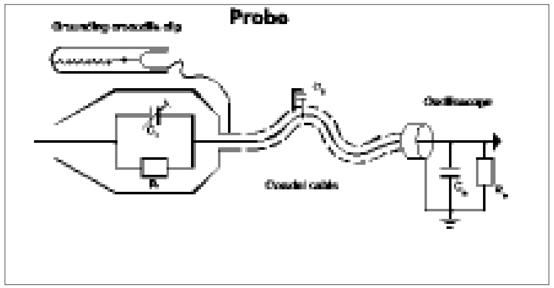


Figure 1.3

If the input impedance of an oscilloscope causes too large load on a signal source with high impedance (i.e. if the scope impedance is much smaller than the source impedance), an attenuating probe must be used. Attenuating probes have a series resistor connected to the signal path, causing resistive voltage division. Usually, the signal coming to the oscilloscope has amplitude of 1/10 or 1/100 (-20 or -40 dB) of the original signal. In order to keep the signal undistorted at all frequencies, the variable capacitor in the probe is used to set the ratio of the measurement circuit capacitances (probe + oscilloscope) the same as the resistance ratio. The trimming affects both the shape and amplitude of the displayed signal. The probe must be re-trimmed every time it is connected to a different channel, because even in the same oscilloscope the capacitances of the different channels may vary from each other. Trimming is easiest using the internal calibration voltage of the oscilloscope. Its output is usually about 1kHz square wave. The probe is trimmed so that the calibration signal looks undistorted. When a direct probe (X1) is used, trimming does not have any effect, since the resistor and capacitor in the X10 probe are bypassed. Thumb rule for selecting a probe: combined impedance of the probe and oscilloscope must be at least two orders of magnitude higher than the impedance of the measured circuit, e.g. 100 MΩ.

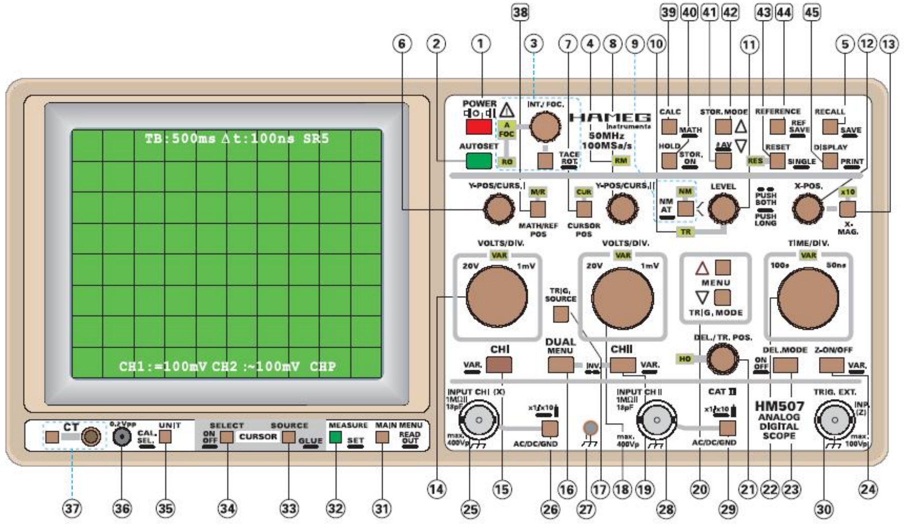
2.1.4 Oscilloscope measurements

The shields of the cables of the different oscilloscope channels are connected together inside the oscilloscope. Therefore it should be noticed that when the cables are connected to the measurement points, their shields must be connected to the same potential also in the measured object. In many oscilloscopes, the shields of the measurement wires are connected to the protective earth of the power supply network. Then you must always make sure that the shields are at the same potential in the measured object and that they do not cause a short-circuit from any live parts to the protective ground. If the measured object is wanted to be kept apart from the protective ground, you must either connect the oscilloscope to the network through a decoupling transformer, or use an oscilloscope with internal decoupling.
Oscilloscope has certain bandwidth and rise time. These quantities express how rapid signals can be displayed correctly. The limitations must be taken into account when examining signals with high frequencies and rapid changes. Thumb rule is that the rise time of the oscilloscope should be less than one fifth of the shortest time interval to be measured. In addition to this one must consider whether the oscilloscope loads the measured object and whether the measurement wires are suitable for the measurement in question.

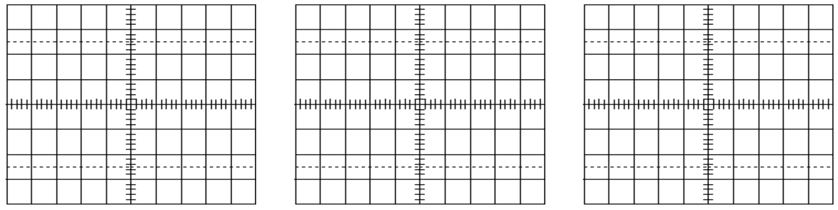
2.2 Pre-report

Answer the following questions before coming to the laboratory.

1. In picture below there is the front panel of the oscilloscope used in laboratory. Mark the following controls/switches in the picture:
- Channel 2 vertical deflection control
- Time deflection control
- Channel selection switches
- Calibration signal connector
- AC/DC and GND switches for channel 1
- Analog/digital mode switch (STOR ON)



2. Suppose that you should use an oscilloscope to examine a square wave (__—__—) of 1 kHz frequency, the upper voltage level 2 V and the lower 0 V. Which scaling do you choose for horizontal and vertical deflections when you want the signal to be displayed as high as possible and at least for two periods? Vertical deflection can be selected from the range of 5mV...5V and horizontal deflection from the range of 0,5 µs...0,5s (see **Vertical deflection**). Zero level has been adjusted to the middle of the screen. What does the signal look like on the screen when the channel is a) DC, b) AC, c) GND coupled? **Draw signals into figures below**.



DC AC GND

3. Explain the effect of adjusting the triggering level and selecting the triggering slope to the oscilloscope function. Explain also the meaning of the triggering modes AUTO, NORMAL and SINGLE.

4. Consider a dual-channel oscilloscope. How is the drawing of the signals to the screen carried out when the vertical deflection of the oscilloscope is in a) alternating mode (ALT) b) chopped mode (CHOPPED)? c) When is it reasonable to use the chopped mode for measurement?

5. Why is it good to use an attenuating probe for oscilloscope measurements? Why is it needed especially at high frequencies? How does non-ideal trimming of a probe affect a high-frequency signal?

2.3 Laboratory exercises

2.3.1 Learning how to use an oscilloscope

Switch the oscilloscope on. Set triggering to channel 1 and make sure that the automatic triggering is on. Adjust the brightness and focus on the screen. Connect 1 kHz sinusoid signal from the function generator to the oscilloscope input. Now try how different controls in the oscilloscope affect the signal shown on the screen.

2.3.2 Probes

Exercise 1

The probes you are given can be used either in direct mode (switch to X1) or attenuating mode (X10). Switch the probe to X1 mode and connect it to channel 1 and to the internal calibration signal of the oscilloscope (pull off the hook connector of the probe and push the head of the probe into the hole marked CAL below the screen). Make sure that trigger signal is set to the channel you are using. What does the calibration signal look like, what are its voltage levels and frequency?

Exercise 2

Test the effect of the AC and DC couplings on the position of the signal on screen. What is the signal's position relative to the zero level of the scope when AC coupling is used?

Exercise 3

Switch the probe to attenuating mode. What is the effect of the attenuation on the amplitude of the calibration signal on the screen? Adjust the probe's trimmer using the small screwdriver so that the calibration signal is seen as undistorted as possible. Trimmer is the little screw on the side of the probe or in the oscilloscope side end of the cable.

Exercise 4
Make sure that both of the probes are ideally trimmed. Connect both of the probes in attenuating mode (X10) to the cable connected to the function generator (cable should be found on the table). Remember to connect the grounding crocodile dip to the zero conductor!
Set the function generator to sinusoid signal, frequency to 100 Hz and amplitude to 1 V. Switch the oscilloscope into dual channel mode. Test the effect of the unideal trimming of the probe to the signal shown on the screen as follows: change the trimming of the probe connected to channel 2. Use both probes to measure the signal from the function generator. Use the oscilloscope settings to show both signals on top of each other on the screen and change the frequency up to 1 MHz. Do the phases and amplifications of the channels remain similar to each other? Why?

Does the unideal trimming have any effect on the signal when the probe is in unattenuating mode (X1)? Why?

Use the calibration signal to trim the probes ideally. Make sure that the signals on both channels are the same at all frequencies.

2.3.3 Low frequency signals

Exercise 5
Switch the HAMEG oscilloscope to digital mode (STORAGE ON). Set the function generator to give 0,1 Hz sinusoidal wave and switch the probes to X1 mode. Set channel 1 DC coupled and channel 2 AC coupled. Adjust their vertical deflections so that both signals are about the same height on the screen and their waveforms are clearly shown.
How do the signals differ from each other?

Change the waveform to triangular. What kind of signals do you see now on both channels?

Change to square wave. What are the signals like?

What is the cause of the differences you saw?

Set the function generator to sinusoidal wave, frequency to 1 kHz, switch the oscilloscope back to the analog mode, set the horizontal and vertical deflections properly for the sinusoid and switch the equipment off.

2.3.4 Signal generator card

Switch the signal generator card on by pressing the switch between the battery and LED! Use the Kenwood oscilloscope.
Exercise 6
Connect a probe to pin 1. Find the signal on the oscilloscope screen (trigger source is Ch 1). Connect the other probe to pin 2. What is the time difference between the rising edges of these two signals? Switch the oscilloscope to take trigger signal from channel 2. What happened?

Exercise 7
What is the waveform, peak value and period of signal 7? Switch the oscilloscope to manual triggering (auto-trigger off). Remember to trig from the correct channel. How does adjusting the trigger level affect the signal on the screen? Test triggering from both rising and falling slope (slope +/-). What is the effect?
Set the probe from X1 to X10 and back. Compare the shape of the signal between these situations.

Exercise 8
What is the waveform of signal 3? How long is its period? Try different coupling modes. Try also the HOLDOFF control.