

The Oscilloscope

1. Introduction

The oscilloscope is basically a graph-displaying device – it draws a graph of an electrical signal. In most applications the graph shows how signals change over time: the vertical (Y) axis represents voltage and the horizontal (X) axis represents time.

First generation of oscilloscopes had as display device the cathode ray tube. Fundamentally an analog oscilloscope works by applying the measured signal voltage directly to an electron beam moving across the oscilloscope screen (usually a cathode-ray tube, CRT). The back side of the screen is treated with a coating that phosphoresces wherever the electron beam hits it. The signal voltage deflects the beam up and down proportionally, tracing the waveform on the screen. The more frequently the beam hits a particular screen location, the more brightly it glows. This gives an immediate picture of the waveform. There were CRTs with memory and the oscilloscopes equipped with such tubes were called CRT oscilloscope with analog memory. Another step forward was the digital CRT oscilloscope that stores the information in electronic memory circuits. Hybrid oscilloscopes are based on analog to digital converters followed by character generators that display some parameters on the CRT.

The last generation of oscilloscopes is completely digital. They are complex data acquisition systems with large memory capacity so they do not lose the acquired information.

2. The one channel classical oscilloscope

A block diagram of the classical oscilloscope is shown in the figure below.

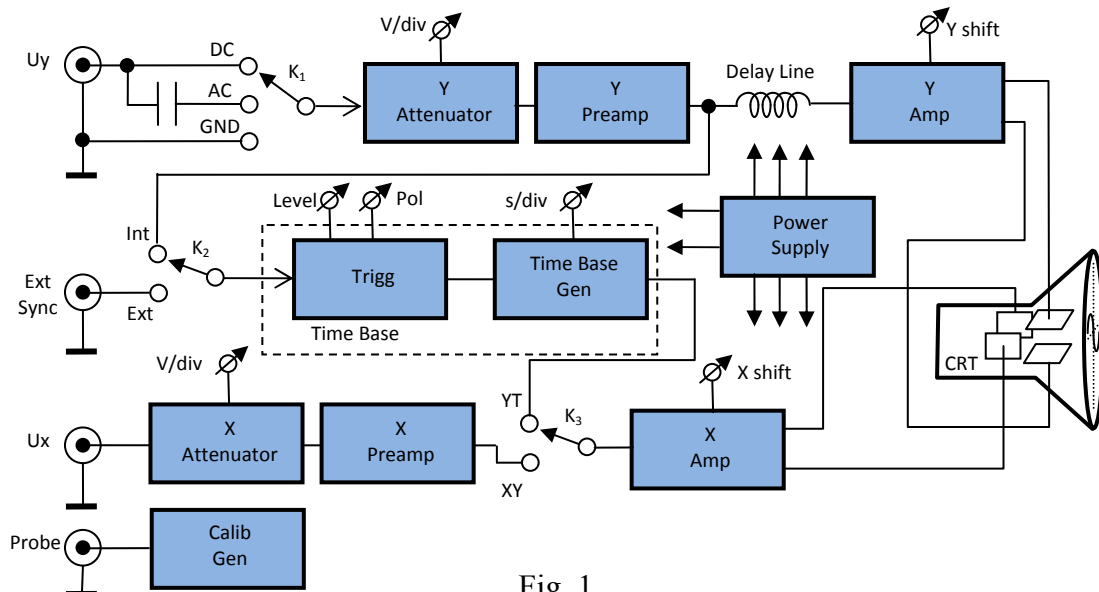


Fig. 1

- a) **Y channel** – its purpose is to apply the signal on the vertical deflection plates:
- *Input coupling switch* – K_1 – allow to choose the way the Y input signal is connected (DC – both alternative and continuous current components, AC – only the alternative current component, GND – the input is connected to the ground in order to establish the zero position of the light spot from *Y shift*)
 - *Y attenuator* – allows the adjustment of the Y channel sensitivity (in steps)
 - *Y Preamp* – amplifies the Y signal. It can have a continuous adjustment of its gain, calibration adjustment, offset compensation or drift compensation circuit.
 - *Y amp* – Y channel final amplifier amplifies the signal up to the level required by the deflection plates. The output is differential for driving each deflection plate. It has a Y shift adjustment for shifting the baseline up and down or for bringing it in the center when the signal has a DC component.
 - *Delay line* – delays the Y signal to compensate the delay that occurs while the time base is triggered, so that the initial part of the signal that triggered the time base is displayed.
- b) **X channel** has the role to apply the signal on the horizontal deflection plates. It has mainly the same building blocks as the Y channel (X attenuator, X preamp and X amp). The input attenuator can miss or it can have only few adjustment steps, the preamp can miss or can be only a repeater. The X channel allows the two working modes (K_3): XY mode – the inputs U_X and U_Y are applied to the deflection plates; YT mode – the signal U_Y is visualized in time mode, the X signal being an internal voltage proportional with time (ramp).
- c) **The time base** – generates a time linear variable wave necessary to visualize $U_Y(t)$.
- *Trigg* – the synchronization circuit produces the necessary pulses for triggering the time base generator (Time Base Gen) in order to have a stable image on the screen. It compares the sync signal ($U_Y - K_2=INT$ or an external voltage – $K_2=EXT$) with a continuous adjustable voltage (Level), and when equal it generates a synchronization pulse that triggers the Time Base generator. This happens always in the same point on the signal curve. The button *Pol* allows selecting the signal slope on which the synchronization point is located.
This block contains also has filter for the sync signal (for complex signals – edge, video, pulse), a self triggering circuit for sweeping the spot when no voltage is applied on U_Y (3 working modes are available – Auto, Trigger, Single).
 - The Time Base Gen – generates the linear variable voltage (saw tooth). The spot sweep starts when this voltage is zero (in the left side of the screen) and continues until the maximum value (the spot is in the right side), then the spot is shut off and is rapidly brought into the initial position to wait for a new sync pulse. The rise time of the linear ramp can be selected from the s/div button, in order to correlate the spot sweeping speed with input signal (U_Y) frequency. The circuit has calibration, stability and extension

adjustment. Some oscilloscopes have a supplementary fast time base used for extending on the whole screen some details from the signal.

- d) **The Power Supply** – generates all the voltages necessary for electronic circuits and for the CRT.
- e) **The Calibration Generator** – it generates a square wave with the frequency of 1kHz and its purpose is to calibrate the Y channel and the time base.
- f) **The CRT (cathode ray tube)** – When switched on, a CRT normally displays a single bright dot in the center of the screen, but the dot can be moved about electrostatically or magnetically. The CRT in an oscilloscope always uses electrostatic deflection. Between the electron gun and the screen are two opposed pairs of metal plates called the deflection plates. The vertical amplifier generates a potential difference across one pair of plates, giving rise to a vertical electric field through which the electron beam passes. When the plate potentials are the same, the beam is not deflected. When the top plate is positive with respect to the bottom plate, the beam is deflected upwards; when the field is reversed, the beam is deflected downwards. The horizontal amplifier does a similar job with the other pair of deflection plates, causing the beam to move left or right. This deflection system is called electrostatic deflection, and is different from the electromagnetic deflection system used in television tubes. In comparison to magnetic deflection, electrostatic deflection can more readily follow random and fast changes in potential, but is limited to small deflection angles. The time base is an electronic circuit that generates a ramp voltage. This is a voltage that changes continuously and linearly with time. When it reaches a predefined value the ramp is reset and settles to its starting value. When a trigger event is recognized, provided the reset process (holdoff) is complete, the ramp starts again. The time base voltage usually drives the horizontal amplifier. Its effect is to sweep the screen end of the electron beam at a constant speed from left to right across the screen, then blank the beam and return its deflection voltages to the left, so to speak, in time to begin the next sweep. Meanwhile, the vertical amplifier is driven by an external voltage (the vertical input).

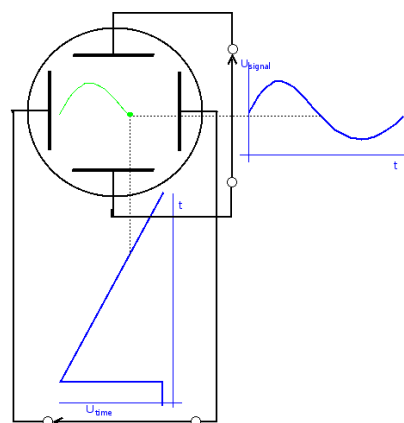


Fig. 2

3. Two-channel oscilloscope

Some applications suppose the simultaneous visualization of more than one signal in order to compare them. One further improvement is the two channel oscilloscope. There are 2 categories of such instruments:

- using CRTs with 2 electron beams and 2 deflection plates
- using a normal CRT and an electronic switch.

The second setup is the most spread because its advantages (simpler CRT construction and one final Y amplifier). Besides dual-beam oscilloscopes had two complete electron guns, requiring tight control of axial (rotational) mechanical alignment in manufacturing the CRT. The schematic diagram of Y channel in the following figure shows how the channel is split before the final amplifier.

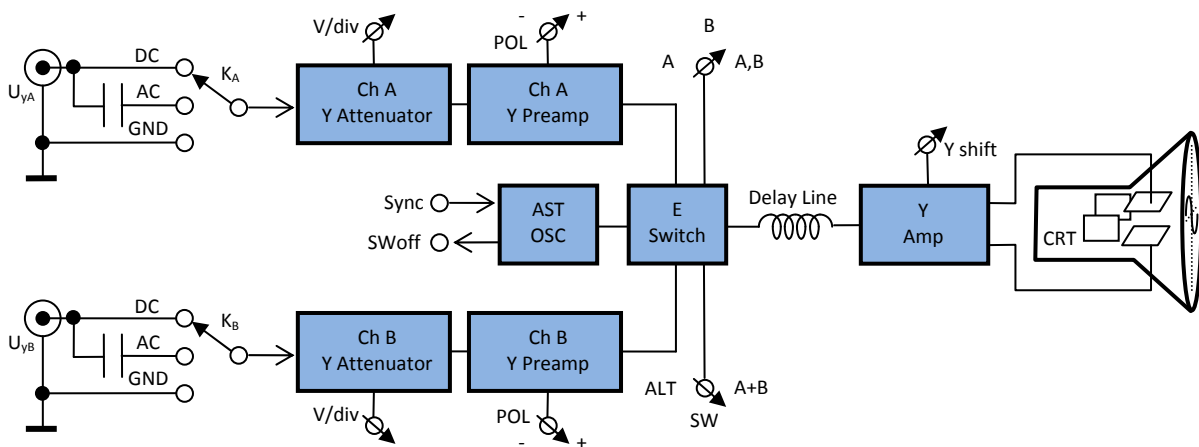


Fig. 3

The voltages U_{yA} and U_{yB} are applied to the electronic switch (E Switch) either with their polarity or with reversed one (POL + or -). The E Switch is driven with a fixed frequency (on mode switched - SW) or with the time base frequency on mode alternate (ALT). On A+B the two voltages are added ($U_{yA} + U_{yB}$). The electronic switch sends to the final amplifier both input signals. The trigger signal can be the channel A, the channel B or a combination of A and B.

The switched mode is used at low frequencies. The signals are represented as dots on the screen. If their frequency is much smaller than the switching frequency they look like continuous curves. The beam is switched off during the transition from one signal trace to the other.

The alternate mode is used at high frequencies. The E Switch is driven with the signal coming from the time base generator. Thus the signal U_{yA} is shown on the first pass of the beam spot and U_{yB} at the second. Because of the human eye inertia and of the screen persistence the curves are seen simultaneously on the screen.

4. Digital storage oscilloscope

The DSO is a complex data acquisition chain. It started with AD and DA conversions and display on CRTs like in the following figure.

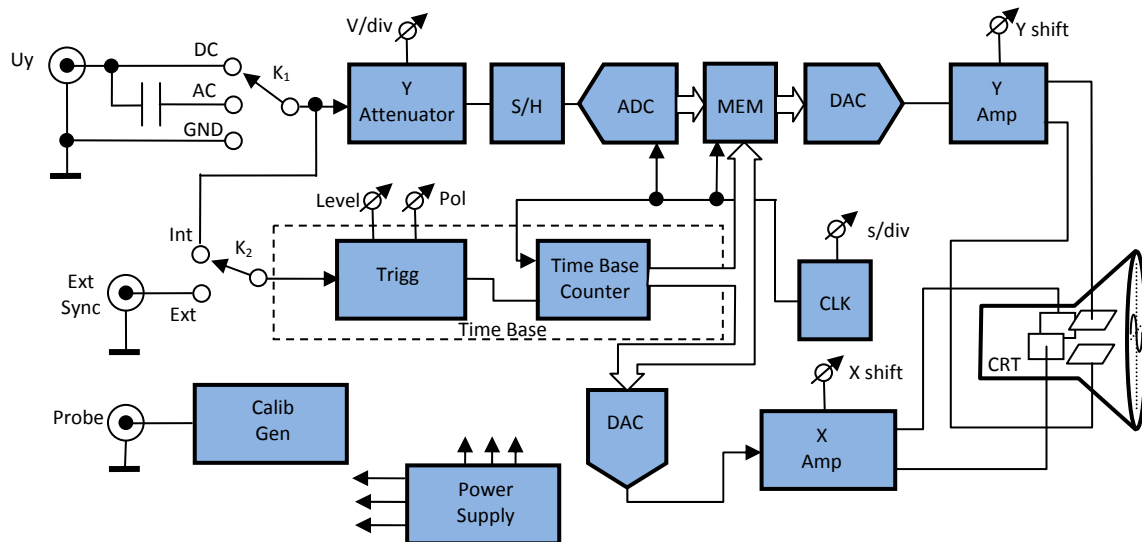


Fig. 4

The Y signal is sampled by the sample & hold (S/H) circuit and then each sample converted to digital by the analog to digital converter (ADC) and is stores them into the memory MEM. The memory content supplies the digital to analog converter with samples correlated with the Time Base Counter that generates the linear variable voltage for the horizontal scan plates. The sampling frequency must respect the Nyquist criteria ($f_s > 2f_m$, where f_s is the sampling frequency and f_m is the maximum frequency of the input signal spectrum). The memory size (C_{MEM}) is correlated with the recording time T_r : $C_{MEM} = f_s \cdot T_r$. The image quality depends on the number of samples and on their resolution. Sometimes the resolution asks for larger conversion times that slow down the acquisition speed. In order to overpass this, an analog memory is added after the S/H circuit (charge coupled device).

5. The oscilloscope with microprocessor

The microprocessor brought many benefits in instrumentation:

- the measurement, processing and display of the data of the process variable are done in real time;
- they have lower costs, higher accuracy and more flexibility;
- they are compact and have low power consumption;
- they can be operated from complex control panels and can display high resolution screens;
- they can do drift corrections, noise reduction, non-linearity corrections, gain adjustments, range and span adjustments, automatic calibration, etc;
- they can have built-in diagnostic routines, which can detect fault and automatically correct them or generate alarms;
- they can store data or save data on additional memories;
- they can be remote controlled via various interfaces.

The last generation of oscilloscopes has 2 sections: waveform recorder section and the analysis and display section.

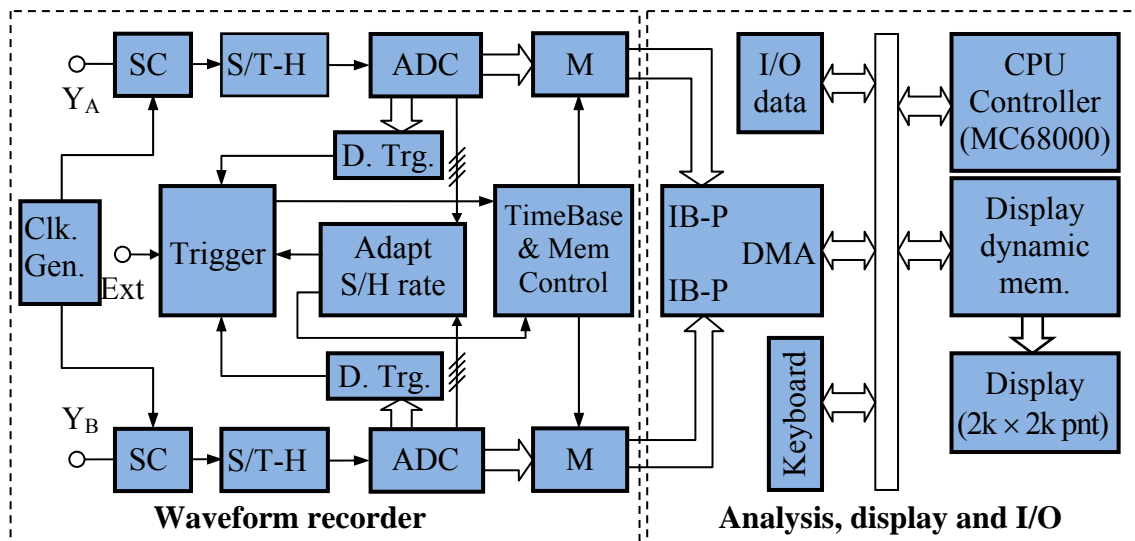


Fig. 5

It has built-in functions as oscilloscope, universal counter, wattmeter and spectrum analyzer. The signal is analog up to the S/H circuit input. The sampling and the analog to digital conversion is achieved with high speed circuits (2 - 4GS/s). The CRT display has been replaced with TFT displays (2048x2048 matrix). The oscilloscope in the figure above has 2 input channels and it is organized in 2 parts: the waveform recorder and the analysis, display and IO part.

The Waveform recorder has:

- *Signal conditioner* SC (attenuator and input preamplifier) – has a decade voltage divider and a voltage differential amplifier with adjustable gains (1, 2, 5), resulting a dynamic range of 100 – 120 dB;
- *Sampling and hold circuit and analog to digital converter* – it uses ultrafast sampling circuits and ADCs capable of up to 10^9 conversions/s and resolutions of 8 to 12 bits. Sometimes 2 such ADCs are used in order to double the sampling rate, the sampling moments being interlaced. For increasing the bandwidth, in some oscilloscopes the input signal frequency band is split in 2 using 2 pass-band filters: the lower band being acquired with a slower ADC and the upper band being down-converted first (translated to the lower band) and then converted with the same lower ADC. The original signal is rebuilt from its samples;
- *High speed memory* – data storage is done immediately the conversion ended. Usually it is a SRAM type and it is controlled by a counter. Data are reorganized in a high capacity dynamic RAM after being filtered and oversampled 8 times in order to improve the resolution;
- *Trigger circuit* (analog and digital, internal or external) – starting from the ADC output samples it provides the trigger level which is not affected by drift or noise;

- *S/H rate adapter* – using digital filtering detects the high frequency transitions and changes the sampling rate according to the signal bandwidth. When not necessary the sampling rate is decreased saving the memory.
- *Internal oscillator and time base* – allows adjusting the sampling rate according to the Nyquist criterion. The time base selects the display time in steps from ns to s. The oscillator is an important part of the instrument because a phase noise of 40ps can generate a distortion of 0.5 bits;
- *Digital control unit* – listen to display analysis and IO unit;

The display, analysis and IO unit includes:

- *CPU* (central processing unit) – it controls the system according to the firmware or to the commands given from the keyboard (front panel);
- *IO port* – is a communication interface (IEEE488, USB, Ethernet) having speeds from 250kB/s to 1MB/s;
- *Display* – it is usually a TFT/LCD display with 2000x2000 points. On the screen, together with the waveform, the oscilloscope display other information like signal frequency, peak, mean or RMS values, vertical and horizontal sensitivity, trigger level, or other menus.

6. Probes for oscilloscopes

The probe is an interface between the signal source and the oscilloscope input. It has to transmit the signal without changing it and without influencing the signal source. For usual oscilloscopes, the covered bandwidth is from DC to 1GHz. Up to 100MHz the probe is a passive RC divider (fig. 6.a). For frequencies higher than 100MHz, but lower than 500MHz, the probe needs HF compensation according to the cable length (fig. 6.b).

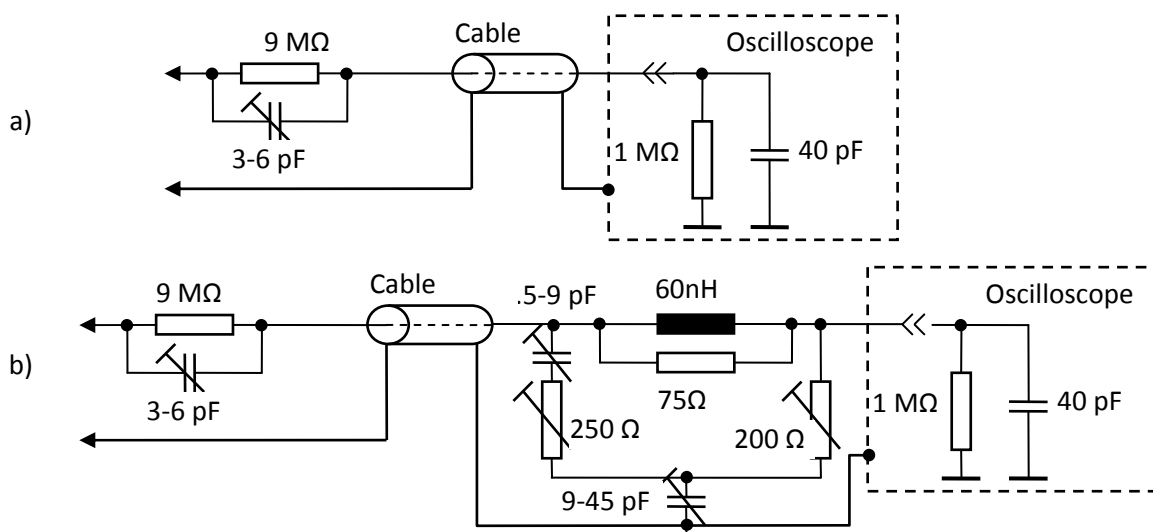


Fig. 6

For even higher frequencies passive compensation is not possible. The probes for higher frequencies are active and must adapt the high input impedance of the oscilloscope to a low impedance of the source (50 or 75 ohms). An active probe has a low input capacitance, high input impedance, high gain and large bandwidth. The input stage is usually a FET.

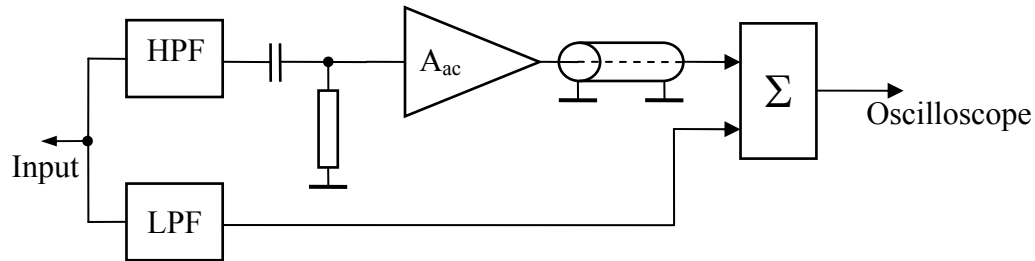


Fig. 7

7. The use of oscilloscopes in measurements

Using its own time base the oscilloscope shows the signal variation in $Y(t)$ because:

$$Y = K_Y U_Y \quad ; \quad X = K_X t \Rightarrow y(x) \leftrightarrow y(t).$$

Quantities like ac voltage (1μV – 100V) with frequencies from DC to 1GHz can be visualized. The image allows estimating the positive and negative peaks of the signal, the DC component, the mean value or the true RMS value, the signal frequency, the rise or fall time, the modulation degree, the phase shift or even the signal spectrum. Signals can be repetitive or not, for non repetitive being useful the working mode with trigger and single run.

a) voltage measurements

- the true RMS value

$$U = \sqrt{U_{cc}^2 + U_{ca}^2} \quad ; \quad U = \sqrt{\frac{1}{T} \int_T u^2(t) dt}$$

where U_{dc} is the DC component and U_{ac} is the true RMS value given by the variable component.

- the mean value

$$\bar{U} = \frac{1}{T} \int_T u(t) dt = U_{cc} \quad (a); \quad U_{med} = \frac{1}{T} \int_T |u(t)| dt \quad (b)$$

- the peak to peak value

$$U_{PP} = U_{max} - U_{min}$$

For any waveform the following inequalities are available:

$$\bar{U} \leq U_{med} \leq U \leq U_m \leq U_{vv}$$

The signal can be characterized by 2 parameters:

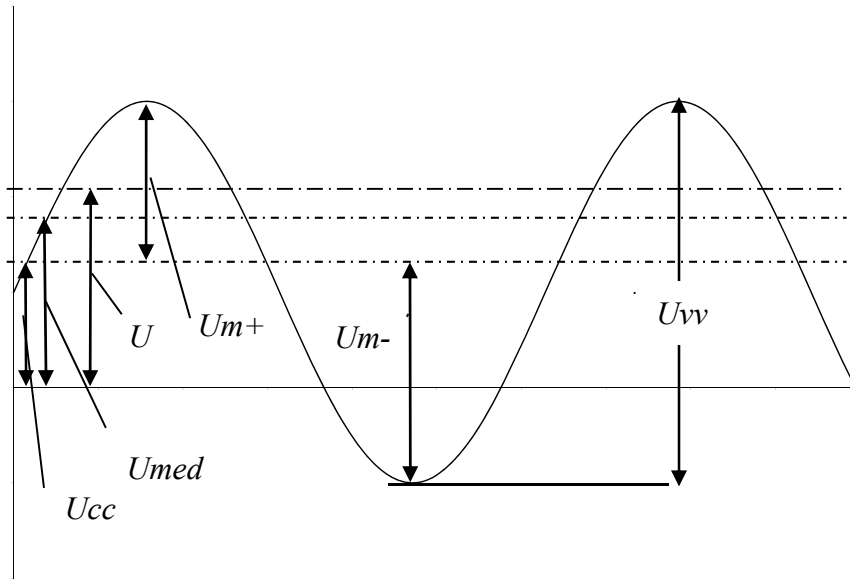


Fig. 8

- the waveform factor: $K_w = \frac{U}{U_{med}} \geq 1$;
- the peak factor: $K_a = \frac{U_m}{U} \geq 1$;

Always $K_a \geq K_w$: $\frac{K_a}{K_w} = \frac{U_m / U}{U / U_{med}} = \frac{U_m U_{med}}{U^2} = \frac{\frac{1}{T} \int U_m |u(t)| dt}{\frac{1}{T} \int u^2(t) dt} \geq 1$.

On the screen the length L_Y [V], between the maximum point of the waveform and the minimum point of the waveform on vertical axis, is measured. The oscilloscope constant K_{Yn} is:

$$U_{Y(m \text{ sau } v-v)} = L_Y K_{Yn}$$

If the signal is symmetric then $U_m = U_{Ym} = U_{Yvv}/2$. Knowing K_a (for a sinus wave for example) the RMS value can be determined:

$$U = U_m / K_a.$$

Knowing the waveform factor K_w , the mean value is:

$$U_{med} = \frac{U}{K_w} = \frac{U_m}{K_a K_w}$$

K_a and K_w for various signals are presented in the Appendix.

a) frequency, phase shift and modulation degree measurements

The frequency is directly measured by knowing the sweep constant K_s of the time axis. Using the internal reference generator (1kHz square wave) K_s must be checked. The length between two peaks or between two passes through zero in the same direction is measured L_x :

$$T_x = K_b L_x \text{ (a); } f_x = 1/T_x \text{ (b)}$$

For a more precise measurement it can be used the Lissajous figures method (less used) or using the substitution method: the input is connected at a signal generator that gives a signal with adjustable frequency. The frequency is tuned until the same number of periods is obtained on the screen. Modern oscilloscopes measure the frequency and display the value on the screen.

Phase shift measurement depends on how many channels the oscilloscope has. The single channel oscilloscope is used in XY mode. The signals are applied at y, respectively at X input. The image is an ellipse but it can be at limits a line or a circle for particular phase shifts ($\pm 180^\circ, 0, \pm 90^\circ$). The phase shift is $\varphi = \pm \arcsin \frac{b'}{b} = \pm \arcsin \frac{a'}{a}$.

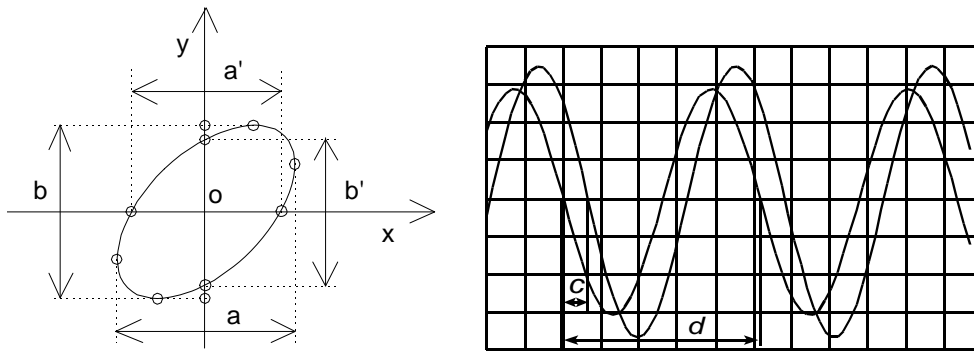


Fig. 9

For the time shift measurement using the oscilloscope with 2 channels both signals must be applied at the inputs of each channel and segments c and d must be measured on the screen. The phase shift is:

$$u = U \sin \omega(t + \tau) = U \sin(\omega t + \varphi) \Rightarrow \varphi = \omega \tau = 2\pi \frac{\tau}{T} = 2\pi \frac{K_b c}{K_b d} = 2\pi \frac{c}{d}$$

The modulation degree for AM signals is:

$$u = U_m (1 + m \cdot \sin \omega_m t) \sin(\omega_p t + \varphi)$$

where

- ω_m is the angular frequency of the modulating signal;
- ω_p is the angular frequency of the carrier;

There are 2 methods:

- the direct method – the time base is adjusted until you get an image similar to figure 10.a.
- the trapeze method – the XY mode is use, while on the Y channel is applied the modulated signal and the modulator signal on the input X. The image in figure 10.b it is obtaine don the screen.

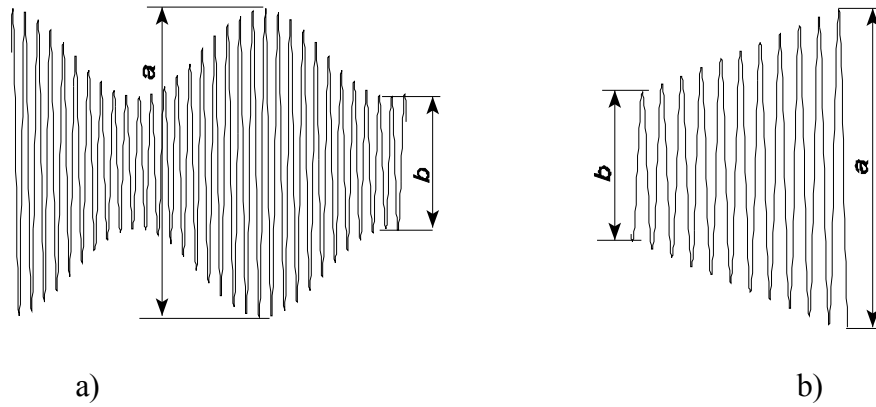


Fig. 10

In both cases the modulation degree is calculated with:

$$a = U_{M_{vv}} = K(1 + m) ; b = U_{\min vv} = K(1 - m) \Rightarrow m = \frac{a - b}{a + b}$$

where $U_{M_{vv}}$ the peak to peak value at the modulated waveform maximum and $U_{\min vv}$ is the peak to peak value at the waveform minimum.

8. Measurements to do in the lab

8.1 Verification of the metrological characteristics

a) deflection coefficients

The vertical deflection coefficient (K_y) must be tested on each sensitivity:

- at the input is applied a signal having the frequency 1kHz and the RMS value (U_y) known with better than 1% accuracy adjusted until the amplitude of the displayed wave is 2n grids.
- The sensitivities S_y and S_x and the deflection coefficients K_y , K_x are:

$$S_y = \frac{L_y}{2\sqrt{2}U_y} \left[\frac{cm}{V} \right] \quad S_{xy} = \frac{L_x}{2\sqrt{2}U_x} \left[\frac{cm}{V} \right]$$

$$K_y = \frac{1}{S_y} \left[\frac{V}{cm} \right], \left[\frac{V}{div} \right] \quad K_x = \frac{1}{S_x} \left[\frac{V}{cm} \right], \left[\frac{V}{div} \right]$$

- the referenced error of the measurement:

$$\varepsilon = 100(K_y - K_{yn})/K_{yn} \text{ or } \varepsilon = 100(K_x - K_{xn})/K_{xn}$$

Table 1 is used to record data:

Table 1

Crt. no.	U_y [V]	L_y [div]	S_y [div/V]	K_y [V/div]	K_{yn} [V/div]	ε [%]	Observations
1							

:							
n							

b) the sweep coefficient

- A signal with well known adjustable frequency is applied at the Y input such as a period of signal must correspond to each grid;
- The sweep coefficient is equal to the signal period;
- the referenced error: $\varepsilon = 100(K_s - K_{sn})/K_{sn}$

Table 2

Crt no..	f [Hz]	v _b [div/s]	K _b [s/div]	K _{bn} [s/div]	ε [%]	Observations
1						
:						
n						

c) the bandwidth

The bandwidth must be tested on the minimum attenuation for channel Y on each connection type: AC and DC.

- a sinus wave is applied from a generator with the amplitude and the frequency known with better than 1% accuracy.
- the frequency is tuned at 1kHz and the voltage to a value $L_y=(n_{max}-2)$ grids. By keeping the voltage constant, the frequency is varied toward DC and respectively higher frequencies until the magnitude on the screen decreases with 3 dB. Thus, the low cut off frequency and the high cut of frequency are obtained.

d) the input impedance

The input impedance is tested for the minimum attenuation for the Y channel.

- a 100Hz sinus signal is applied and its amplitude is adjusted until the amplitude on the screen is $L_y=(n_{max}-2)$ grids U_1 .
- a series resistor it is added between the signal source and the oscilloscope ($R=0,2 \dots 1M\Omega$, 0.5%) and the amplitude is adjusted again until on the screen is the same amplitude U_2 .
- The input impedance is calculate with the formula:

$$\frac{U_1}{U_2} = \frac{R_i}{R + R_i} \cdot \frac{1}{\sqrt{1 + (\omega \cdot R_l \cdot C_i)^2}}; \quad R_l = \frac{R \cdot R_i}{R + R_i}$$

- neglecting the capacitance at 100Hz the input resistance is:

$$R_i = \frac{U_1}{U_2 - U_1} \cdot R$$

- the input voltage is adjusted at $U_3 = \sqrt{2}U_2$ and keeping it constant the frequency is increased until the amplitude becomes again as for U_2 . The capacitance C_i is:

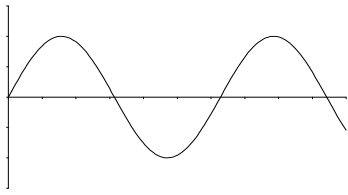
$$\omega_i \cdot R_l \cdot C_i = 1; \quad C_i = \frac{1}{\omega_i \cdot R_l} = \frac{1}{2 \cdot \pi \cdot f_i \cdot R_l}$$

- for the input impedance on channel X the same steps as for channel Y must be followed.

Observation: The frequency band and the input impedance can be found in narrow limits according with the Y attenuator because of the resistors and the capacitances inside the attenuator. In order to check the mismatch of the input impedance a 1:10 probe must be used, adjusted on an attenuator range, and then checked if the compensation is maintained on the other ranges too.

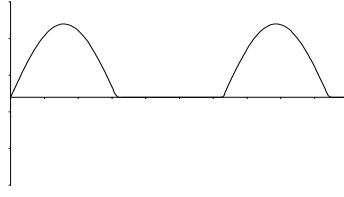
Appendix

$$Ka = \sqrt{2} = 1,414; \quad Kf = \frac{\pi}{2\sqrt{2}} = 1,11$$



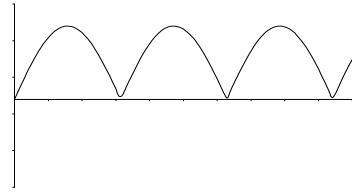
a)

$$Ka = 2; \quad Kf = \frac{\pi}{2}$$



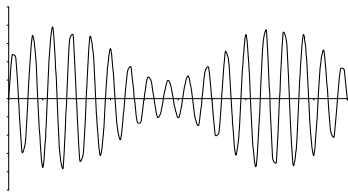
b)

$$Ka = \sqrt{2} = 1,414; \quad Kf = \frac{\pi}{2\sqrt{2}} = 1,11$$



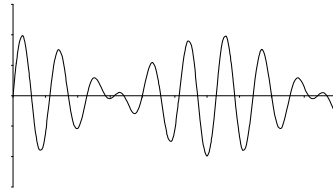
c)

$$Ka = \sqrt{2} \frac{1+m}{\sqrt{1+m^2/2}}; \quad Kf = \frac{\pi}{2\sqrt{2}} \sqrt{1+\frac{m^2}{2}}$$



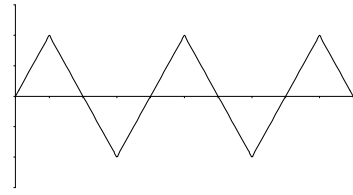
d)

$$Ka = 2; \quad Kf = \pi^2 / 2$$



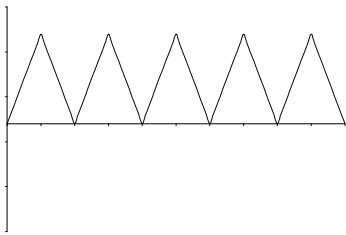
e)

$$Ka = \sqrt{3}; \quad Kf = 2/\sqrt{3}$$



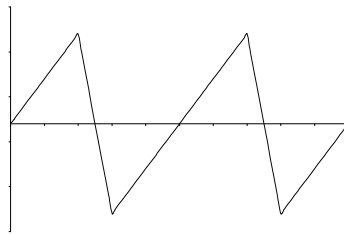
f)

$$Ka = \sqrt{3}; \quad Kf = 2/\sqrt{3}$$



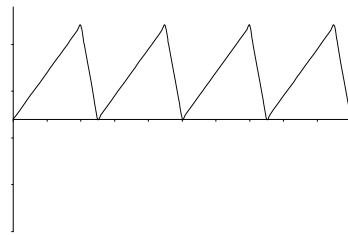
g)

$$Ka = \sqrt{3}; \quad Kf = 2/\sqrt{3}$$



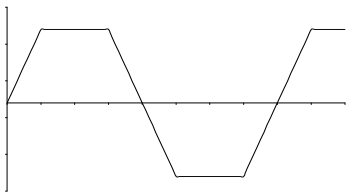
h)

$$Ka = \sqrt{3}; \quad Kf = 2/\sqrt{3}$$



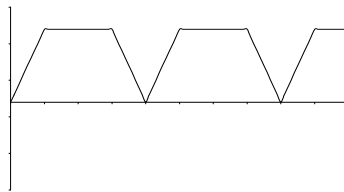
i)

$$Ka = \sqrt{2}; \quad Kf = 8/5\sqrt{2}$$



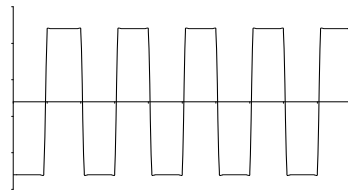
j)

$$Ka = \sqrt{2}; \quad Kf = 8/5\sqrt{2}$$



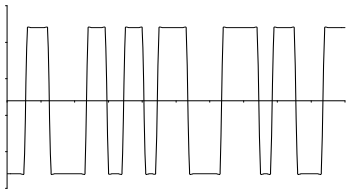
k)

$$Ka = Kf = 1$$



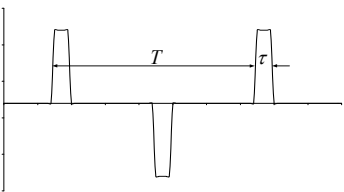
l)

$$Ka = Kf = 1$$



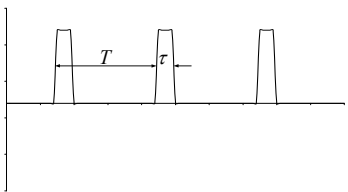
m)

$$Ka = Kf = 1/\sqrt{\eta}; \quad \eta = \tau/T$$



n)

$$Ka = Kf = 1/\sqrt{\eta}; \quad \eta = \tau/T$$



o)

Group

Name

Date

Lab no. 4***The oscilloscope***

Abstract:

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Keywords:.....

Experimental work

1. Testing the vertical sensitivity (figure 1)

Table no. 1

Crt. no.	U_y [V]	L_y [div]	S_y [div/V]	K_y [V/div]	K_{yn} [V/div]	ε [%]	Observations
1		2			0,01		
2		4			0,01		
3		6			0,01		
4		8			0,01		
5		2			0,02		
6		4			0,02		
7		6			0,02		
8		8			0,02		

2. Testing the horizontal sensitivity (figure 1)

Table no. 2

Nr. crt.	U_x [V]	L_x [div]	S_x [div/V]	K_x [V/div]	K_{xn} [V/div]	ε [%]	Observations
1		2			1		
2		4			1		
3		6			1		
4		8			1		
5		10			1		

3. Testing the sweeping coefficient (figure 1)

Table no. 3

Nr. crt.	f [kHz]	Lx [div]	n	v _b [div/s]	K _b [s/div]	K _{bn} [s/div]	ε [%]	Observations
1	1							
2	1							
3	1							
4	10							
5	10							

4. Measuring the bandwidth (a.c.) at -3 dB (figure 1): $f_{\min} = \dots\dots$ Hz; $f_{\max} = \dots\dots$ MHz

5. Input impedance measurement (figure 2)

Table no. 4

Crt. no.	Ly(R=0, f=10Hz)	R [kΩ]	Ly(R, f=10Hz)	Ri [MΩ]	f(Ly*0.707) [kHz]	Ci [pF]	Obs.
1							
2							
3							

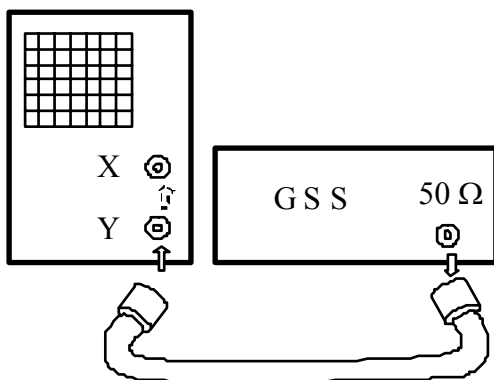


Figure 1

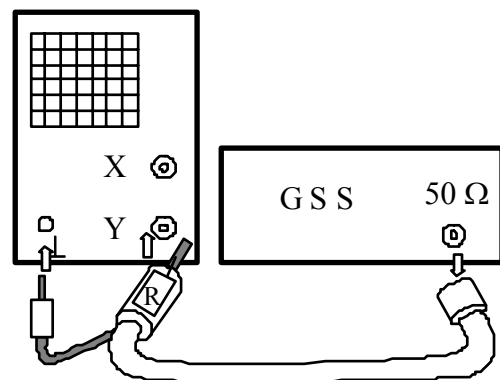


Figure 2

Conclusions:

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