Low Frequency Oscillators

1. General considerations

An oscillator is a single-port electronic circuit (without an input port) that provides a periodic signal at its output by converting direct current energy from the power supply into alternating current energy. Oscillators are used in applications where signal generation is required. In practice, there are two main types of oscillators: harmonic oscillators and relaxation oscillators. In the case of harmonic oscillators, the output signal is sinusoidal. In the relaxation oscillators the signal generated can be in a saw tooth, triangular, rectangular or can have a particular shape. A harmonic oscillator consists of an amplifier and a positive feedback network. The positive feedback network is connected between the output terminals and input terminals of the amplifier, and it has the role of determining the occurrence and maintenance of oscillations. It has a selective transfer characteristic in the frequency domain as it contains reactive elements (L and / or C). In general, in the construction of the positive feedback network are used:

- R and C type components (RC oscillators) for low frequencies (below 1MHz);
- L and C type components (LC oscillators) for high and very high frequencies (100KHz-1GHz);
- quartz crystals (quartz oscillators), for frequencies between 10kHz and 100MHz.

2. Condition of oscillations. The Barkhausen criterion

Typically, in the architecture of an oscillator, in addition to the mandatory positive feedback network, the signal amplifier may also have its own negative feedback network. A general block diagram of an oscillator will comprise an amplifier block without feedback ($\underline{a}$) and two feedback circuits (loops): a negative feedback circuit ($\underline{f}$) and a positive feedback circuit($\underline{\beta}$) (Fig.1).

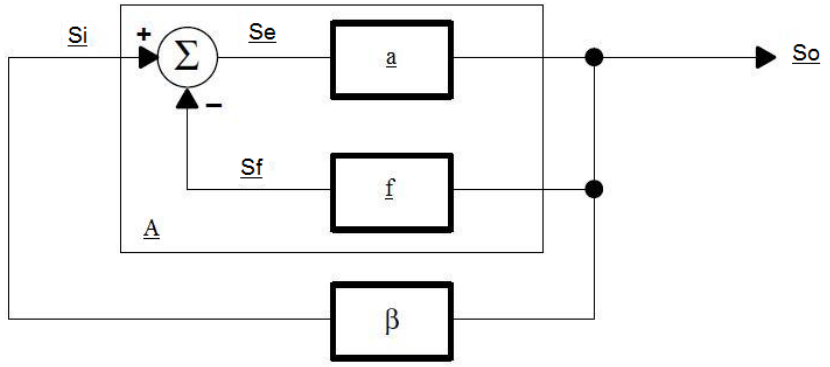

Fig.1 The block diagram of an oscillator

These feedback circuits usually consist of passive components, but there are also particular situations when active components are introduced into the feedback circuit to improve the electrical performance of the oscillator. The blocks $\underline{a}$ and $\underline{f}$ form a negative feedback amplifier. The magnitude of the gain is given by the equation:

$$\underline{A} = \frac{\underline{a}}{1 + \underline{a} \cdot \underline{f}} = \frac{1}{\frac{1}{\underline{a}} + \underline{f}} \qquad (1)$$

If the open loop gain ($\underline{a}$) is high, then:

$$\underline{A} = \frac{1}{\underline{f}} \qquad (2)$$

By considering the block diagram from Fig.1, the following equations may be written:

$$\underline{S_i} = \underline{\beta} \cdot \underline{S_o} \qquad (3)$$

$$\underline{S_f} = \underline{f} \cdot \underline{S_o} \qquad (4)$$

$$\underline{S_e} = \underline{S_i} - \underline{S_f} \qquad (5)$$

$$\underline{S_o} = \underline{a} \cdot \underline{S_e} \qquad (6)$$

where,

$\underline{S_i}$ - the signal value at the input of the negative feedback amplifier;

$\underline{\beta}$ - the transfer function of the positive feedback network;

$\underline{f}$ - the transfer function of the negative feedback network;

$\underline{S_o}$ - the value of the signal at the output of the negative feedback amplifier;

$\underline{S_f}$ - the value of the signal at the output of the negative feedback circuit;

$\underline{S_e}$ - the value of the signal at the input of the open loop amplifier.

From Eqs. (3)-(6) it results:

$$\underline{S_o} = \underline{a} \cdot \left(\underline{\beta} \cdot \underline{S_o} - f \cdot \underline{S_o} \right) \qquad (7)$$

and by division with $\underline{S_o}$:

$$\underline{\beta} = \frac{1}{\underline{a}} + \underline{f} \qquad (8)$$

Noticing that the equation (8) is the inverse of the expression (1), it results:

$$\underline{A} \cdot \underline{\beta} = 1 \qquad (9)$$

Relation (9) represents the Barkhausen condition of occurrence of oscillations in a circuit. If this condition is fulfilled, the circuit can maintain a permanent oscillation regime. Because transfer functions are in the complex domain, Barkhausen's criterion can be described by two relations in which we will treat separately the modules and phases of these complex functions. (10-11):

$$\left|\underline{A}\right| \cdot \left|\underline{\beta}\right| = 1 \qquad (10)$$

or: the product of the modules of the gain and of the transfer function of the positive feedback network is equal to 1.

$$\varphi_{\underline{A}} + \varphi_{\underline{\beta}} = 2k\pi, \;\; k \in \mathbb{Z} \qquad (11)$$

or: the sum of the phase shifts introduced by the amplifier and the positive feedback network is a multiple of 2π.

It was stated at the beginning of this paragraph that the signal amplifier may also have a negative feedback network, but this is not absolutely mandatory. A circuit can oscillate even if it does not have a negative feedback network (Fig.*2*).

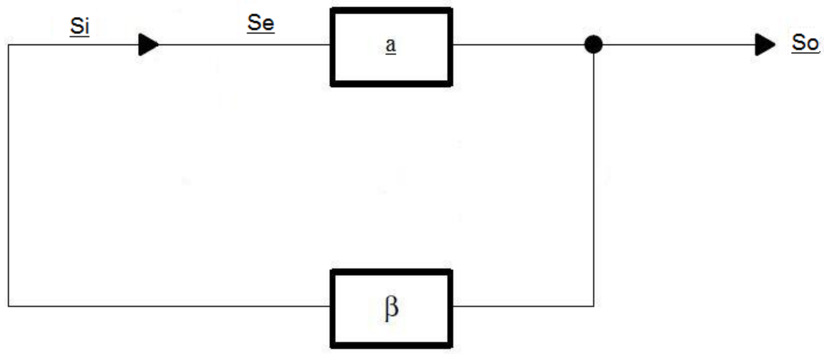

Fig.2 The block diagram of an oscillator in which the amplifier does not contain a negative feedback loop

The block $\underline{a}$ is an amplifier without negative feedback, and the block $\underline{\beta}$ is a positive feedback circuit. Since there is no negative reaction, relations (3-6) are rewritten for $\underline{S_f} = 0$ and the following equation is obtained:

$$\underline{S_o} = \underline{a} \cdot \underline{\beta} \cdot \underline{S_o} \qquad (12)$$

By division with $\underline{S_o}$ is determined the Barkhausen condition, valid also for this type of oscillator:

$$\underline{a} \cdot \underline{\beta} = 1 \qquad (13)$$

3. Low frequency RC oscillators

In the present paper, only low frequency RC oscillators are studied experimentally. The operation of two types of oscillators is analyzed:

- RC oscillators with phase change ;
- Wien bridge oscillators.

Both types of these oscillators are based on low power amplifiers built with bipolar junction transistors.

3.1 RC oscillator with phase shift

In Fig.3 is presented a classic RC oscillator (with a phase shift network). The oscillator is composed of a simple amplifier built with a bipolar transistor in the common emitter connection and an RC type phase shift network. The output of the oscillator is the same as that of the amplifier and it is on the collector of the BJT. The input of the amplifier is in the base of the transistor. The positive feedback network consisting of 3 RC phase cells has the input connected to the transistor collector, and the output is at the base of the transistor. Each cell will introduce a 60^0 sinusoidal signal phase shift, which will cause a total phase jump of 180^0 over the entire positive feedback network. Considering that the phase shift on the common emitter stage is 180^0, the total phase shift will be 360^0, being fulfilled the phase condition from Barkhausen's criterion for the occurrence of oscillations.

.

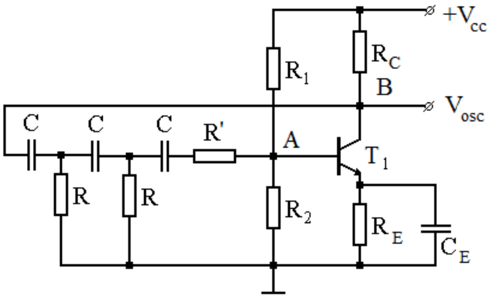

Fig.3 Phase shift oscillator

By noting with A the node in the base of the transistor and with B the node in the collector (Fig.3), the transfer function of this circuit can be written as:

$$\underline{\beta}(\omega) = \frac{\underline{V_A}}{\underline{V_B}} \tag{14}$$

The equivalent resistance at the base of the bipolar transistor consists of $R_1||R_2||r_{BE}$. The resistor R' is chosen so that, at the occurrence of oscillations $R_1||R_2||r_{BE} + R' = R$.

The analysis of the positive feedback network will be performed on the diagram in Fig.4. A positive feedback network consisting of identical filter-type RC cells was considered to pass above the 3rd order, and the output impedance in the transistor collector was zero (Rc has a very low value).

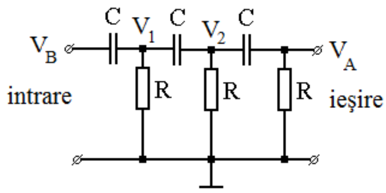

Fig.4. The phase shift network

An RC cell will have a complex impedance:

$$\underline{Z}(\omega) = R + j \cdot X_C \tag{15}$$

where, $X_C = \frac{1}{\omega C}$

The module of the complex impedance is:

$$|\underline{Z}(\omega)| = \sqrt{R^2 + X_C^2} \tag{16}$$

The phase shift introduced by the cell is:

$$\Delta\varphi(\omega) = arctan\frac{X_C}{R} \tag{17}$$

By considering V1 and V2 the voltages in the intermediate nodes (Fig.III.01.4), we have that:

$$\underline{\beta}(\omega) = \frac{\underline{V_A}}{\underline{V_B}} = \frac{\underline{V_A}}{\underline{V_2}} \cdot \frac{\underline{V_2}}{\underline{V_1}} \cdot \frac{\underline{V_1}}{\underline{V_B}} \tag{18}$$

where,

$$\frac{\underline{V_A}}{\underline{V_2}} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{j\omega RC}{1 + j\omega RC} \tag{19}$$

$$\frac{\underline{V_2}}{\underline{V_1}} = \frac{j\omega C}{j\omega C + \frac{1}{R} + \frac{1}{R + \frac{1}{j\omega C}}} = \frac{j\omega RC\left(1 + j\omega RC\right)}{1 + 3j\omega RC + \left(j\omega RC\right)^2} \tag{20}$$

$$\frac{\underline{V_1}}{\underline{V_B}} = \frac{j\omega C}{j\omega C + \frac{1}{R} + \frac{1}{\frac{1}{j\omega C} + \frac{1}{\frac{1}{R} + \frac{1}{\frac{1}{j\omega C} + R}}}} = \frac{j\omega RC\left[1 + 3j\omega RC + \left(j\omega RC\right)^2\right]}{1 + 5j\omega RC + 6\left(j\omega RC\right)^2 + \left(j\omega RC\right)^3} \tag{21}$$

By replacement in Eq. (18) the transfer function is obtained:

$$\underline{\beta}(\omega) = \frac{\left(j\omega RC\right)^3}{1 + 5j\omega RC + 6\left(j\omega RC\right)^2 + \left(j\omega RC\right)^3} = \frac{-j\left(\omega RC\right)^3}{1 - 6\left(\omega RC\right)^2 + j\left[5\omega RC - \left(\omega RC\right)^3\right]} =$$

$$= \frac{\left(\omega RC\right)^3}{\left[\left(\omega RC\right)^3 - 5\omega RC\right] + j\left[1 - 6\left(\omega RC\right)^2\right]} \tag{22}$$

The module of the transfer function is:

$$\left|\underline{\beta}(\omega)\right| = \frac{\left(\omega RC\right)^3}{\sqrt{\left[\left(\omega RC\right)^3 - 5\omega RC\right]^2 + \left[1 - 6\left(\omega RC\right)^2\right]^2}} \tag{23}$$

You get:

$$\left|\underline{\beta}(\omega)\right| = \frac{\left(\omega RC\right)^3}{\sqrt{\left(\omega RC\right)^6 + 26\left(\omega RC\right)^4 + 13\left(\omega RC\right)^2 + 1}} \tag{24}$$

At the oscillation frequency f_0, the imaginary part of the transfer function is zero, ($Im\left\{\underline{\beta}(\omega_0)\right\} = 0$). As such, $1 - 6\left(\omega_0 RC\right)^2 = 0$. So:

$$\left(\omega_0 RC\right) = \frac{1}{\sqrt{6}} \tag{25}$$

The oscillation frequency is obtained:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi RC\sqrt{6}} \tag{26}$$

By using the relation (24), the modulus of the transfer function is calculated:

$$\left|\underline{\beta}(\omega_0)\right| = \frac{\left(\omega_0 RC\right)^3}{\sqrt{\left(\omega_0 RC\right)^6 + 26\left(\omega_0 RC\right)^4 + 13\left(\omega_0 RC\right)^2 + 1}} = \frac{1}{29}. \tag{27}$$

From the Barkhausen's criterion (13), it results that the value of the voltage gain for the bipolar transistor amplifier in the EC connection has its module equal to 29 so that the circuit can maintain a permanent sinusoidal regime.

The phase shift introduced by an RC cell at the oscillation frequency is:

$$\Delta\varphi(\omega_0) = arctan\frac{1}{\omega_0 RC} = arctan\frac{1}{2\pi RC \cdot f_0} \quad (28)$$

By replacing f_0 it is obtained:

$$\Delta\varphi(\omega_0) = arctan\sqrt{6} \approx 60^0 \quad (29)$$

The following important aspects remain to be emphasized:
- the output impedance of the amplifier (resistance Rc) was neglected in solving the above equations;
- the gain of the transistor is strongly dependent on the static operating point (DC bias);
- the operation of the transistor at low signal is no longer valid (the amplitude of the sinusoidal voltage $\underline{V_{be}}$ is much higher than $\underline{V_{th}}$), as such the high signal model of the transistor is adopted;
- the transistor dynamically modifies its current gain as a function of time during a period of the sinusoid;
- the oscillation frequency is influenced by the modification of the static operating point, which determines the modification of the base-emitter resistance of the transistor;
- the output voltage of the oscillator is of the order of volts, but it cannot exceed the value of the DC supply voltage.

Modeling the bipolar transistor in forward active regime at large signal involves using the following set of equations that approximate its operation:

$$i_C = \beta \cdot i_B \quad (30)$$

$$i_C = I_S \, exp\left(\frac{v_{BE}}{V_{th}}\right)\left(1 + \frac{v_{CE}}{V_A}\right) \quad (31)$$

where I_S is the saturation current, and V_A is the Early voltage that models the change of the base thickness according to the collector-emitter voltage variations. The current gain of the bipolar transistor decreases compared to the situation when the transistor is used at small signal. In the large signal model, the B-E junction is replaced by a diode in forward bias regime, and the C-E junction is replaced by a current generator (Fig.5).

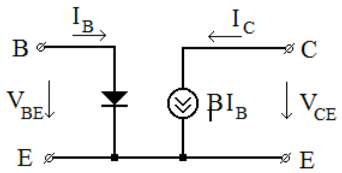

Fig.5 The BJT circuit at large signal.

Another phase shift oscillator configuration is shown in Fig.3.6, where the positioning of the capacitors and resistors is reversed. The feedback network is a 3rd order low pass filter with identical RC circuits. The transfer function is determined in a similar way to the previous case. The oscillation frequency is:

$$f_o = \sqrt{\frac{6}{2\pi RC}} \quad (32)$$

The RC oscillator is used to generate signals that have a frequency between a few Hz and up to hundreds of KHz. It is not as efficient for generating megahertz frequencies. In order to vary the frequency of the oscillator as wide as possible, the three capacitors (or the three resistors) must be varied simultaneously. Only in this way the impedance of the network is kept constant and therefore the amplitude of the oscillations does not change. The amplifiers used for these oscillators are generally in A class so that the output signal has a low distortion coefficient.

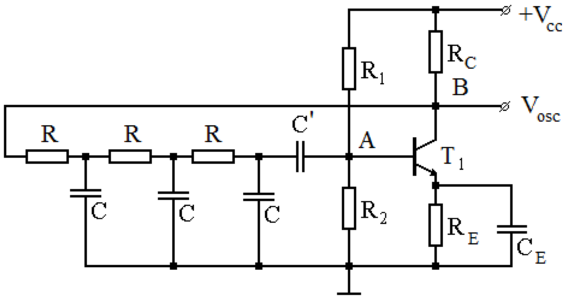

Fig.6 Phase shift oscillator (second version).

3.2 Phase shift problems in the oscillator design

The positive feedback circuit consists of RC cells. A single cell can provide a maximum phase shift of 90^0. Two cells can provide a maximum phase shift of 180^0. The phase shift determines the oscillation frequency, as the circuit will oscillate at any frequency at which the phase shift introduced by the positive feedback network is 180^0. The phase shift change with frequency $\left(\frac{\Delta\varphi}{\Delta\omega}\right)$ determines the frequency stability of the oscillator. If the positive feedback network consists of only 2 RC type cells, then a small variation of the phase shift will create instability in the oscillator operation by the situation when the phase shift is less than 180^0, because the second condition of Barkhausen's criterion is not fulfilled. By adding a supplementary RC cell (a total of 3 RC cells) solves this problem, and the stability of the oscillations is ensured from this perspective.

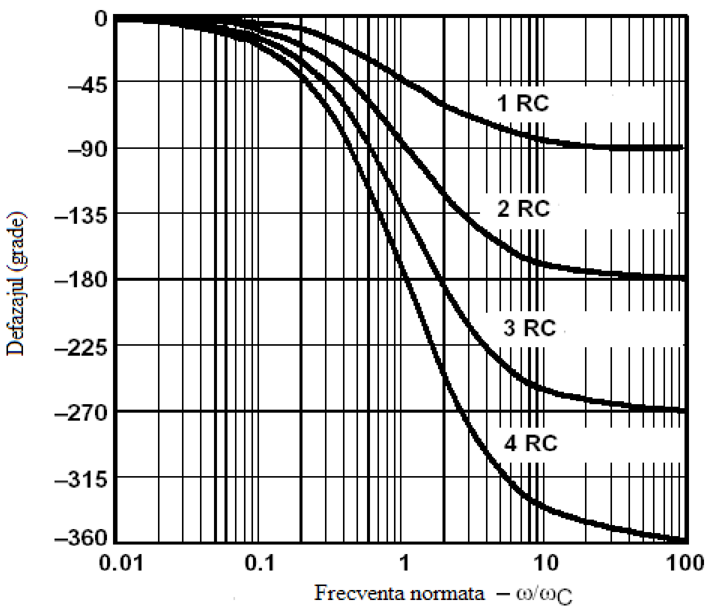

Fig.7 The frequency dependence of the phase shift for several RC cells.

3.3 The Wien Bridge oscillator

The Wien bridge oscillators are RC oscillators that use a selective RC network with a band-pass transfer function. In Fig.8 is depicted the basic circuit of this type of oscillator. An operational amplifier in the non-inverting configuration is used in this circuit (the signal from the positive feedback network C1-R1-C2-R2 is applied to the non-inverting input marked with +, and the signal from the negative feedback network R3-R4 is applied to the inverting input marked with -).

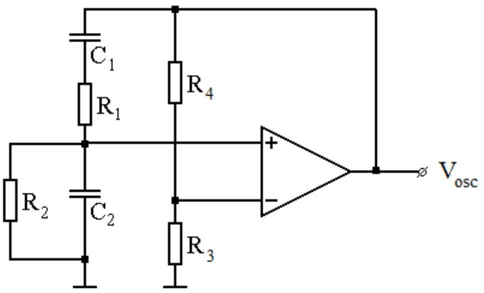

Fig.8 The block diagram of a Wien bridge oscillator built with an operational amplifier.

The operational amplifier (with the symbol represented in Fig.9) is a voltage amplifier. Its output voltage is proportional to the differential input voltage measured between the non-inverting input (marked with +) and the inverting input (marked with -). The proportionality factor is the differential gain. This circuit is typically an integrated circuit. An operational amplifier structure can also be made with discrete components, but its electrical performance would be inferior to an integrated structure.

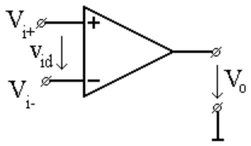

Fig.9 The operational amplifier

The main features of the operational amplifier are:

- The open loop voltage gain a_v (without feedback) is very high, of the order of thousands, tens or hundreds of thousands;
- the input currents (non-inverting input current and inverting input current) are very small, of the order nA or even pA for general purpose operational amplifiers;
- the input resistance is very high, of MΩ order or even higher;
- the output resistance is very low, theoretically zero (the operational amplifier behaves at the output as an ideally controlled voltage generator).

The negative feedback amplifier section from Fig.8 is represented in Fig.10. The voltage gain is determined on the circuit from Fig.10. Whereas (the currents through the input terminals are very low):

$$\underline{V_{id}} = 0 \qquad (33)$$

The following equations may be written:

$$\underline{V_i} = R_3 \cdot \underline{I} \qquad (34)$$

$$\underline{V_O} = R_4 \cdot \underline{I} + R_3 \cdot \underline{I} \qquad (35)$$

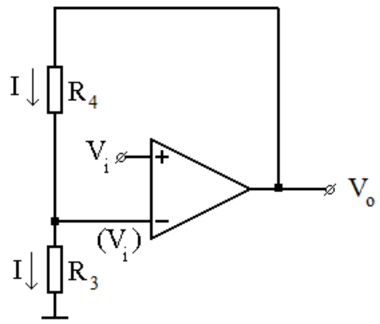

Fig.10 An operational amplifier in the non-inverting configuration

The voltage gain of the circuit is:

$$\underline{A_V} = \frac{\underline{V_O}}{\underline{V_i}} = \frac{R_4 \cdot \underline{I} + R_3 \cdot \underline{I}}{R_3 \cdot \underline{I}} = \frac{R_4 + R_3}{R_3} = 1 + \frac{R_4}{R_3} \tag{36}$$

The voltage transfer Wien bridge (Fig.11) is composed of 2 resistors and 2 capacitors (the input of the network is connected to the output of the amplifier, the output of the network is connected to its input - as such we "repositioned" in this analysis separate from the context $\underline{V_i}$ and $\underline{V_o}$):

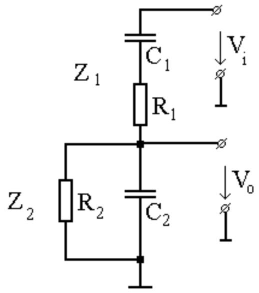

Fig.11 The Wien bridge.

The transfer function of the circuit from Fig.11 is:

$$\underline{\beta(\omega)} = \frac{\underline{V_o}}{\underline{V_i}} = \frac{\underline{Z_2}}{\underline{Z_1} + \underline{Z_2}} \tag{37}$$

where

$$\underline{Z_1} = R_1 + \frac{1}{j\omega C_1} \quad \text{și} \quad \underline{Z_2} = R_2 \left\| \frac{1}{j\omega C_2} \right. \tag{38}$$

After some calculus it results:

$$\underline{\beta(\omega)} = \frac{1}{1 + \frac{R_1}{R_2} + \frac{C_2}{C_1} + j\left(\omega R_1 C_2 - \frac{1}{\omega R_2 C_1}\right)} \tag{39}$$

The module of the transfer function is:

$$\left|\underline{\beta(\omega)}\right| = \frac{1}{\sqrt{\left(1 + \frac{R_1}{R_2} + \frac{C_2}{C_1}\right)^2 + \left(\omega R_1 C_2 - \frac{1}{\omega R_2 C_1}\right)^2}} \tag{40}$$

The phase of the transfer function is given by:

$$\Delta\varphi(\omega) = -arctg \frac{\omega R_1 C_2 - \frac{1}{\omega R_2 C_1}}{1 + \frac{R_1}{R_2} + \frac{C_2}{C_1}} \quad (41)$$

The equation (39) shows that the Wien bridge has a selective behavior in the frequency domain justified also by the amplitude-frequency characteristic from Fig.12 The phase shift on the Wien bridge is zero if the imaginary part of the expression (39) is canceled. As a result there will be a single frequency f_o for which:

$$\omega R_1 C_2 - \frac{1}{\omega R_2 C_1} = 0 \quad (42)$$

From Eq. (42) the oscillation frequency is obtained:

$$f_o = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \quad (43)$$

At the oscillation frequency the transfer function becomes real:

$$\underline{\beta(\omega)} = \frac{1}{1 + \frac{R_1}{R_2} + \frac{C_2}{C_1}} \quad (44)$$

If the Wien bridge elements are equal ($R_1=R_2=R$, $C_1=C_2=C$), then:

$$f_o = \frac{1}{2\pi RC}, \ \underline{\beta(\omega_0)} = \frac{1}{3} \quad (45)$$

Fig.12 shows the amplitude-frequency characteristic for the module of the voltage transfer function of the Wien bridge.

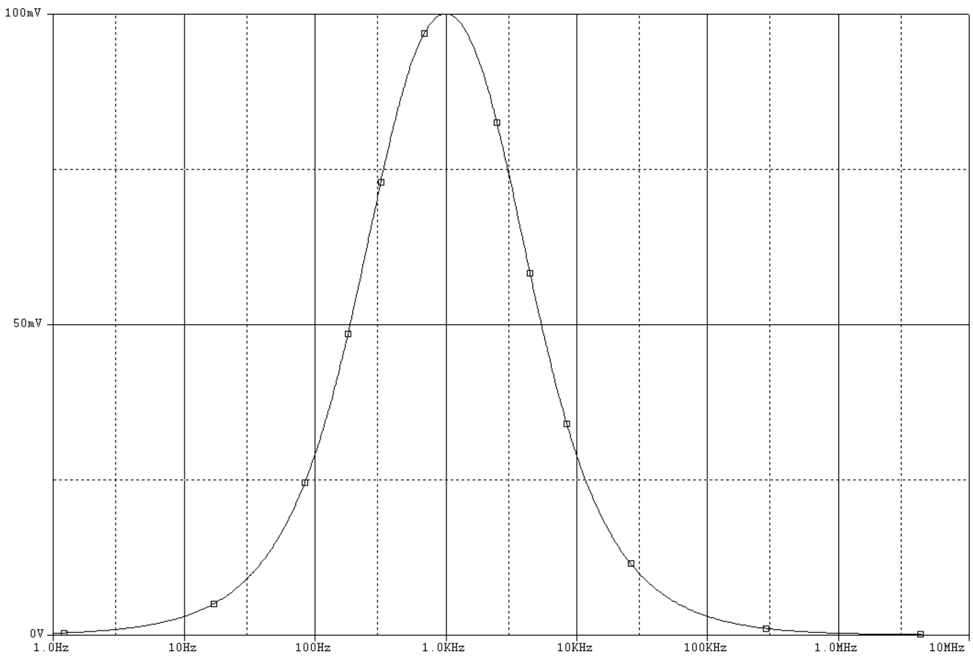

Fig.12 The module of the transfer function

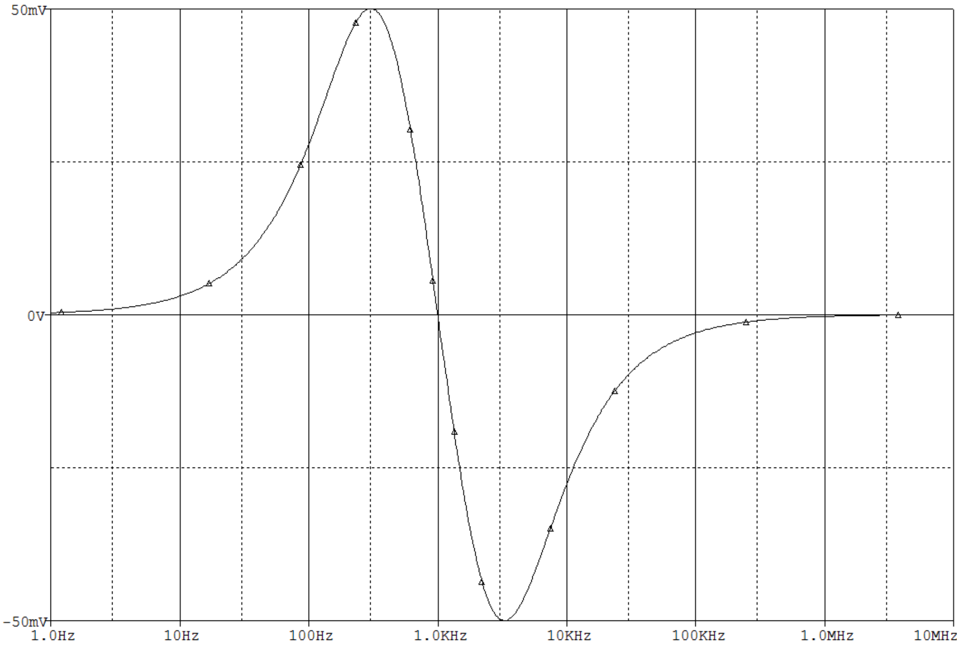

Fig.13 The phase of the transfer function

The circuit from Fig. 8 will maintain a permanent sinusoidal regime (will be a harmonic oscillator) if the conditions mentioned in the equations (10-11) are fulfilled. Knowing that the gain is given by the Eq.(36) and the module of the transfer function of the Wien network at the oscillation frequency is 1/3, it turns out that:

$$R_4 = 2 \cdot R_3 \qquad (46)$$

Since the phase shift introduced by the Wien bridge is zero, the phase shift introduced by the amplifier will have to be zero in order to meet the phase condition in Eq.(11). The operational amplifier can be replaced with an amplification stage with discrete components (two bipolar transistors).

The following issues are met:

- the input impedance of the amplifier with bipolar transistors is much lower than that of the operational amplifier, which determines a slight increase of the oscillation frequency by decreasing the equivalent resistance connected in parallel R_2;
- the output impedance of the amplifier with transistors is higher than the output impedance of the operational amplifier, which determines a decrease of the oscillation frequency by increasing the resistance equivalent in series with R_1.

3.4 Design issues

If the gain of the amplifier used inside the oscillator is very high ($|\underline{A}| \cdot |\underline{\beta}| > 1$), distortion may occur, and the sinusoidal signal at the output of the oscillator will be distorted. Usually, when there is an increase in the amplitude of the output signal, the amplitudes of the electrical quantities (voltages, currents) at the terminals of the active device (transistor) will increase, which implies a decrease of the current gain (β decreases at high currents), and a decrease of the gain of the amplifier. There is thus an intrinsic negative feedback inside the electronic device (BJT).

If the gain of the amplifier is too small ($|\underline{A}| \cdot |\underline{\beta}| < 1$) the oscillator will not work (there will be no sinusoidal signal generated at its output).

It is recommended that in the most unfavorable conditions (low supply voltage, extreme temperatures, transistor chosen from a batch with low current gain), the amplifier has a gain slightly greater than 1/β, so that the sinusoidal signal is undistorted and the oscillator may operate in any conditions.

3.5 Adaptation issues

The positive feedback network must be designed in such a way as to suit the type of amplifier to which it is applied. For example, if the block A (Fig.1) is a voltage amplifier, the positive feedback network must be a voltage divider (voltage transfer network), so as not to affect the output impedance of the amplifier (to have a very high input impedance). On the other hand, the voltage amplifier must have a high input impedance, so that the transfer function of the positive feedback circuit is not modified.

3.6 The stabilization of the amplitude of the output signal

The structure of the amplifier A (Fig.1) includes active devices that have a non-linear transfer characteristic and a variable gain which is strongly dependent on the amplitude of the output signal.

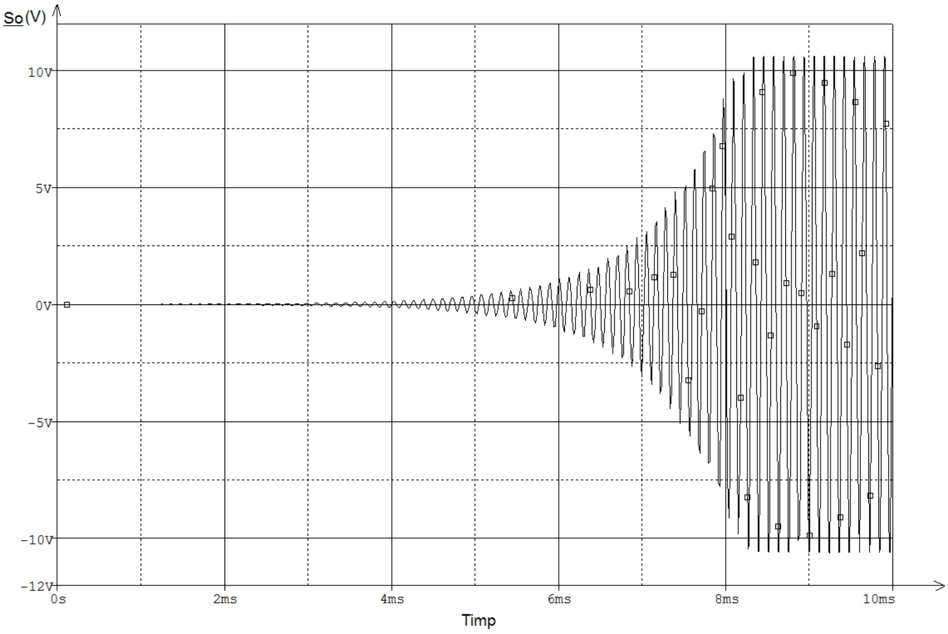

Fig.14 The stabilization of the amplitude of oscillations

Thus, the amplifier gain is high at low amplitude signals, and it has lower and lower values as the signal amplitude increases. The positive feedback circuit β (Fig.1) collects the S_O signal taken from the output of the amplifier A. Then it divides S_O and then applies it to the input S_i. When the DC power supply is connected, the reactive elements (L, C) in the feedback network will have nonlinear changes of currents and voltages at their terminals, which determines the appearance of a variable signal S_i at the output of the feedback network. Since the initial amplitude of the input signal is small, the gain of the active devices is very high, which causes a significant increase in the amplitude of the $\underline{S}_O$ signal at the output. This signal is then divided by the feedback network and applied again at the input of the amplifier in several successive cycles. During each cycle, the amplitude of the output signal increases and the gain $\underline{A}$ decreases, as long as the equation $|\underline{A}| \cdot |\underline{\beta}| > 1$ is valid. When the amplitude of $\underline{S}_O$ becomes very high, the gain decreases and the amplitude of the oscillations is limited ($|\underline{A}| \cdot |\underline{\beta}| = 1$). From this moment on, the oscillations will have constant amplitude (Fig.14).

4. Laboratory activity

4.1 Consider the circuit presented in Fig.15. Draw and simulate it. The parameters should be written in *Table 1*.

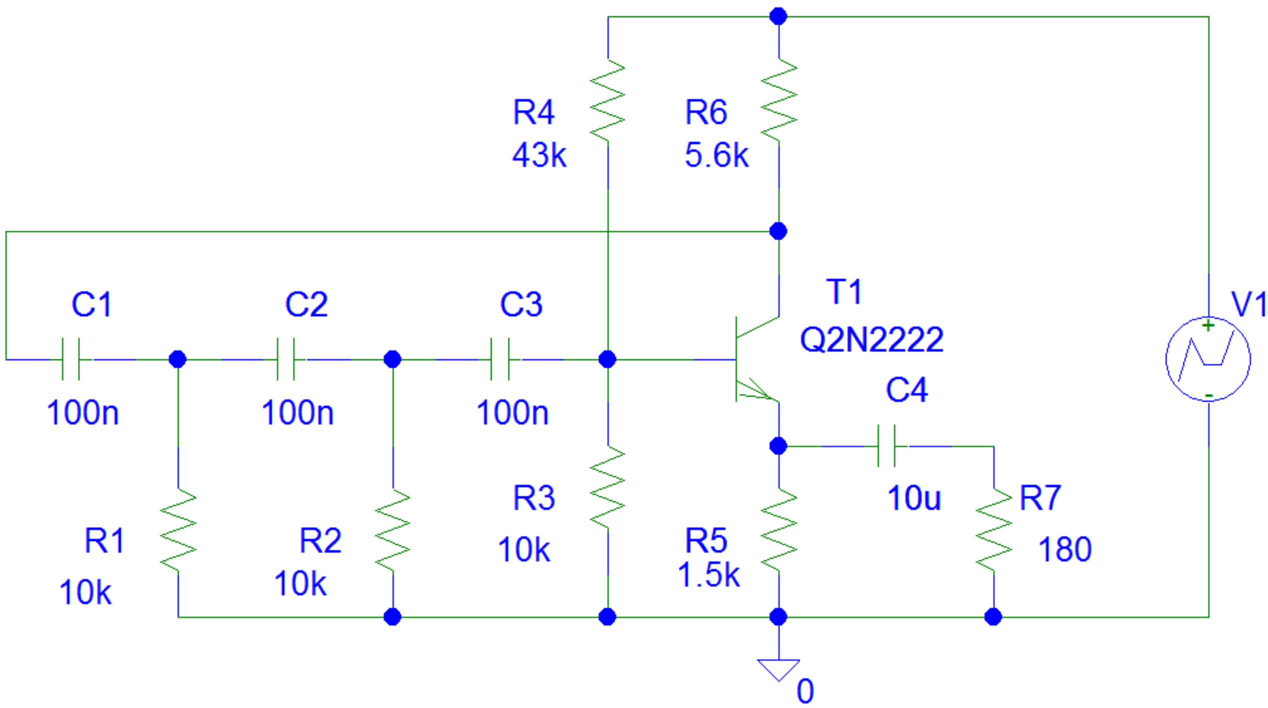

Fig.15 A phase shift oscillator built with a BJT amplifier in a distributed load configuration

Table 1

f_o(KHz)=	
I_{Cmin} (mA)=	I_{Cmax} (mA)=
V_{CEmin} (V)=	V_{CEmax}(V)=
V_{R1}(V)	
V_{R2}(V)	
V_{R3}(V)	
$V_{out\ Q1\_C}$ (V)	
V_{R7}(V)	
$\Delta\varphi_{Q1\_C,R1}$(^{0})	
$\Delta\varphi_{R1,R2}$(^{0})	
$\Delta\varphi_{R2,R3}$(^{0})	

4.2 Consider the circuit presented in Fig.16. Draw and simulate it. The parameters should be written in *Table 2*.

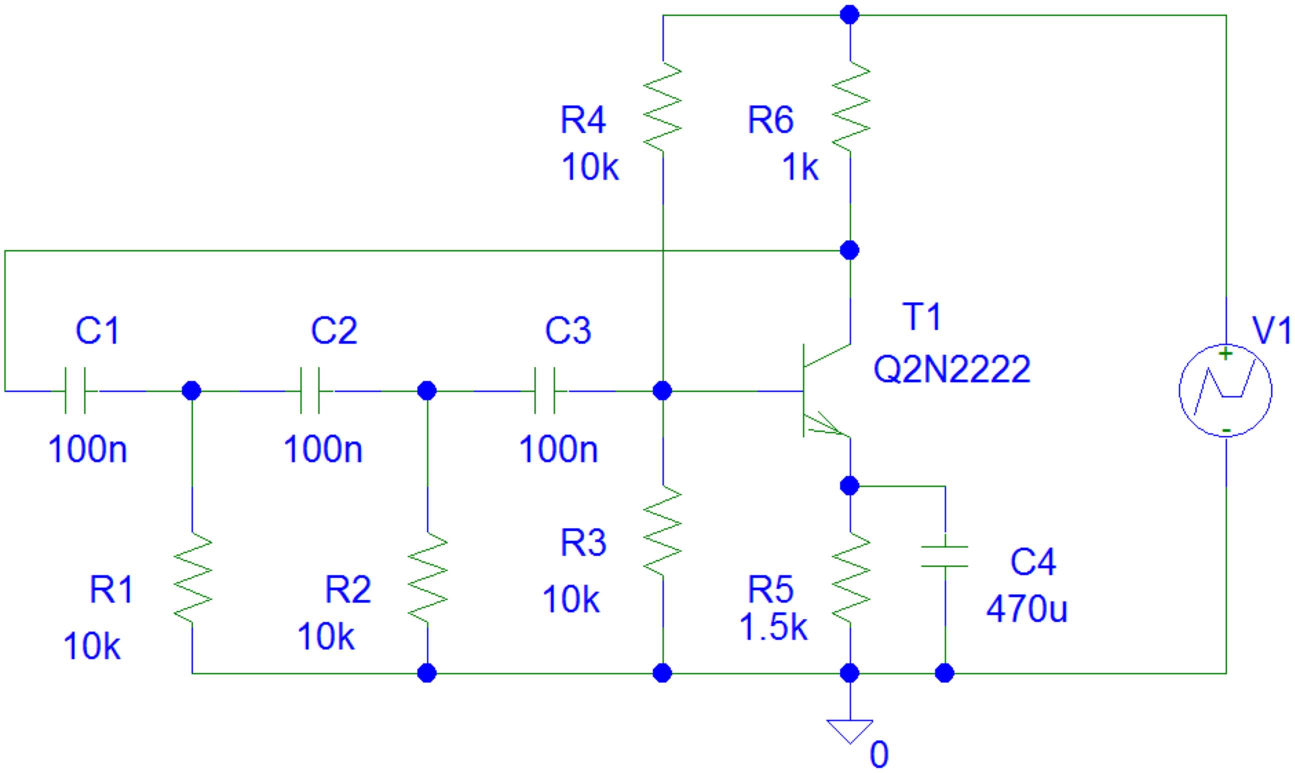

Fig.16. A phase shift oscillator built with a BJT amplifier in a common emitter configuration

Table 2

f_o(KHz)=	
I_{Cmin} (mA)=	I_{Cmax} (mA)=
V_{CEmin} (V)=	V_{CEmax}(V)=
V_{R1}(V)	
V_{R2}(V)	
V_{R3}(V)	
$V_{out\ Q1\_C}$ (V)	
$\Delta\varphi_{Q1\_C,R1}$(^{0})	
$\Delta\varphi_{R1,R2}$(^{0})	
$\Delta\varphi_{R2,R3}$(^{0})	

4.3 Consider the circuit presented in Fig.17. Draw and simulate it. Adjust R9 to obtain the proper shape of the waveform at the output. The parameters should be written in *Table 3*.

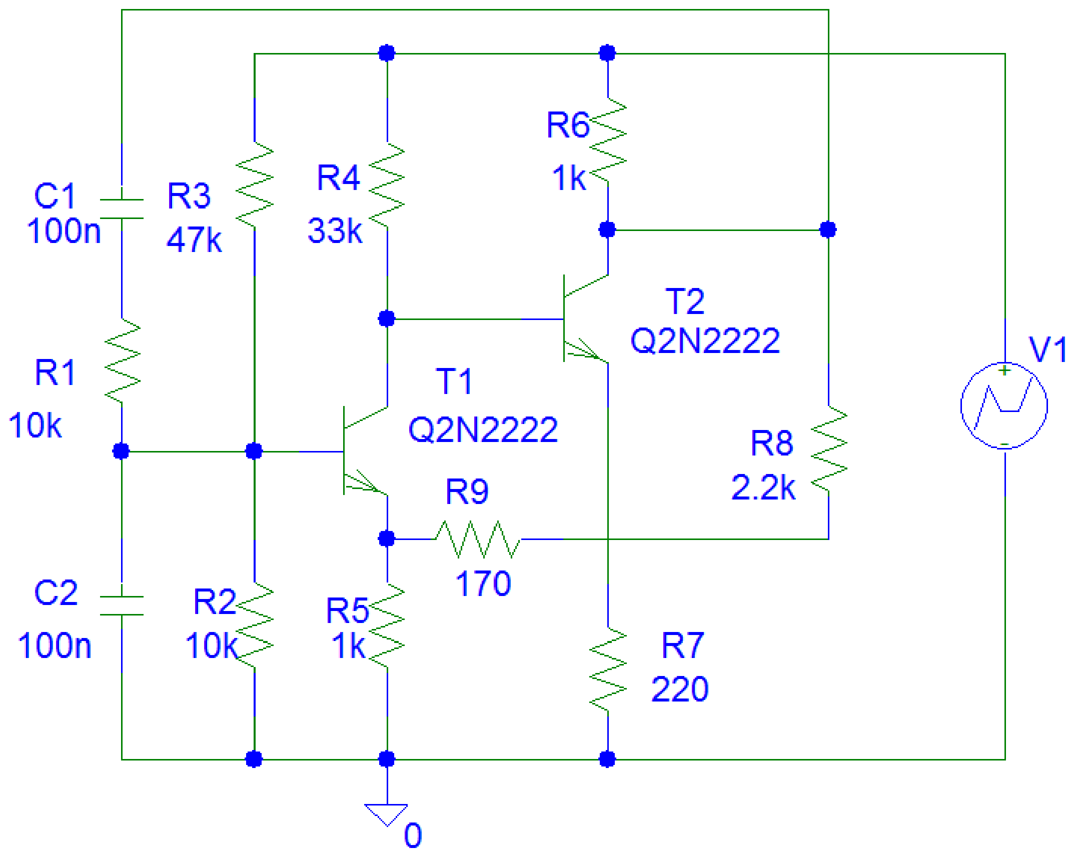

Fig.17. The Wien bridge oscillator

Table 3

Capacitor value	$C_{1,2}$=10nF	$C_{1,2}$=100nF	$C_{1,2}$=1uF
f_o (Hz)			
$V_{RMS\ out}$ (mV)			
$V_{RMS\ in}$ (mV)			
$A_V = \frac{V_{RMSout}}{V_{RMSin}}$			