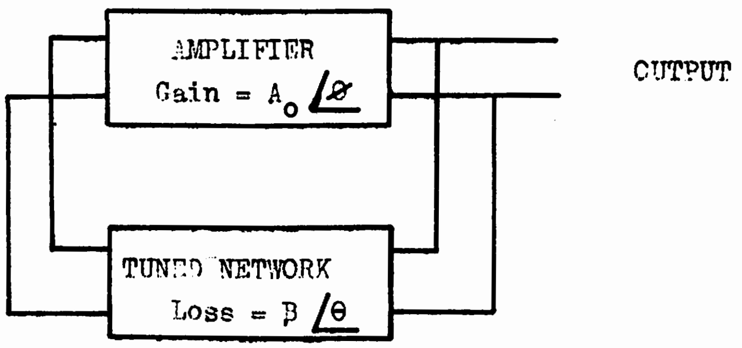
OSCILLATORS

1. Introduction

In this section of the course we are going to consider tuned oscillators which produce a sinusoidal output waveform. Earlier in the course you met the astable multivibrator which produced square waves. These circuits operate in saturated or cut off modes where the frequency of operation is determined by the exponential charge and discharge of a capacitor. Sine wave oscillators, however, consist of an amplifier with a tuned feedback network as shown below :



To obtain a pure sine wave output it is arranged that the gain around the feedback loop is unity at the frequency of oscillation and that the total phase shift is zero.

i.e. Amplifier Gain = Attenuation of Feedback Network

Thus $A_o = \frac{1}{\beta}$

$\beta A_o = 1$

And $(\theta + \varnothing) = 0^\circ$ or 360°

There are two special cases :

a) If the amplifier provides a 180° phase shift ($\varnothing = 180^\circ$)
Then θ must equal 180°.

b) If the amplifier provides a 0° phase shift ($\varnothing = 0^\circ$)
Then θ must equal 0°.

(See appendix for a more detailed discussion of amplifier stability and the necessary conditions for oscillation.)

2. Wien Oscillator

This is based on the Wien Network (See Figure 2.)

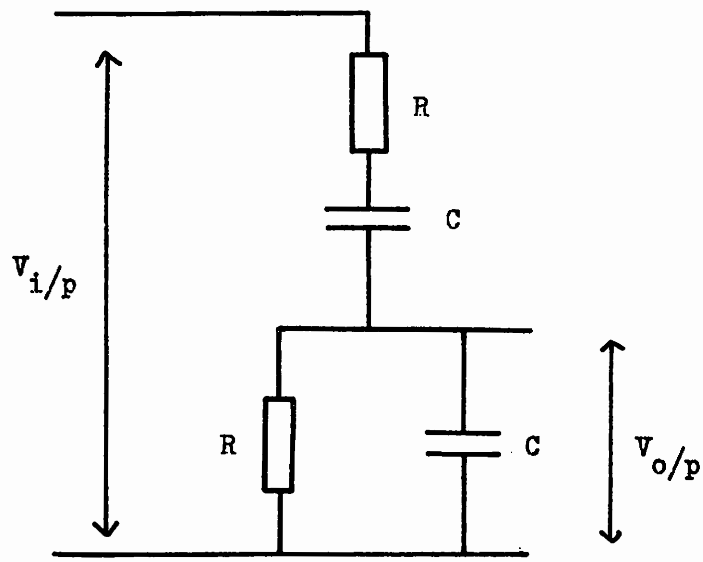


Figure 2

The transmission characteristics of this network may be worked out as follows:

$$Z \text{ of parallel arm} = \frac{R(\frac{1}{j\omega C})}{(R + \frac{1}{j\omega C})}$$

$$= \frac{R}{(j\omega CR + 1)}$$

Thus,

$$\frac{V_{o/p}}{V_{i/p}} = \frac{\frac{R}{(j\omega CR + 1)}}{R + \frac{1}{j\omega C} + \frac{R}{(j\omega CR + 1)}}$$

$$= \frac{R}{(j\omega CR + 1)(R + \frac{1}{j\omega C}) + R}$$

$$= \frac{R}{(j\omega CR^2 + R + R + \frac{1}{j\omega C} + R)}$$

$$= \frac{R}{3R + j(\omega CR^2 - \frac{1}{\omega C})}$$

This will have 0^{o} phase shift at the frequency at which:

$$(\omega C R^{2} - \frac{1}{\omega C}) = 0$$

i.e.

$$R^{2} = \frac{1}{\omega^{2} C^{2}}$$

$$f = \left(\frac{1}{2\pi CR}\right)$$

At this frequency,

$$\frac{V_o}{V_i} = \frac{R}{3R}$$

giving $\beta = \left(\frac{1}{3}\right)$

If this network is connected in the feedback path of an amplifier with a gain of +3, then it can oscillate at the frequency $f = \left(\frac{1}{2\pi CR}\right)$:

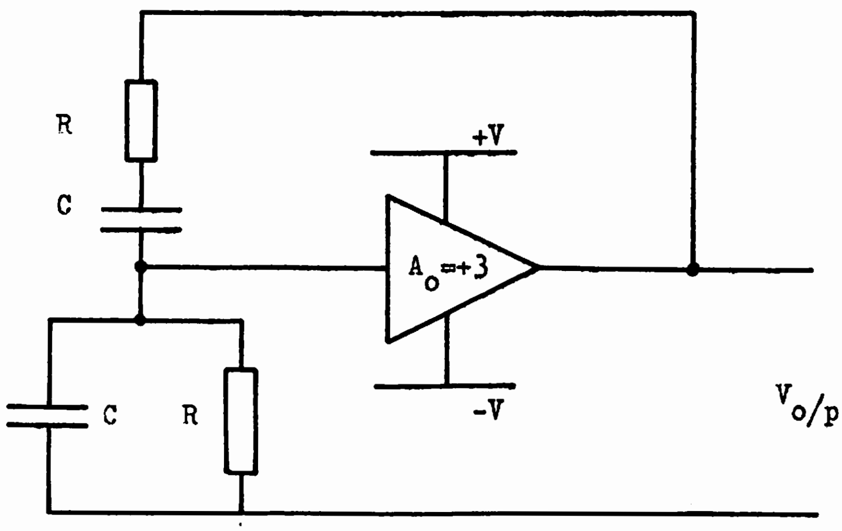


Figure 3

Problem 1

What would be the frequency of oscillation of a Wien Oscillator tuned with R = 10k and C = 100nF?

Problem 2

What value of C would be required to tune a Wien Network to 15 kHz, if R = 5 k?

3. Starting Conditions

If the loop gain ($\beta . A_o$) of the circuit is less than one, the oscillator will not be able to start. If the loop gain is greater than one then there are two main methods by which the oscillations can start:-

a) By the switch-on surge providing the required energy.

b) By random noise, which is always present.

For both of these cases, if this gain is maintained the output will get progressively bigger until the gain is reduced by limiting. This will normally introduce distortion. Remember that in order to produce a pure sinewave we normally need the loop gain to be stabilised at unity.

4. Amplitude Stability

In order to maintain a constant output level from the oscillator it is necessary to control the gain. At switch on we require a loop gain which is greater than unity, falling to unity when oscillations have reached the required amplitude.

In the Wien oscillator the gain can be controlled by varying the negative feedback on the amplifier. This can be done automatically by including a thermistor in the feedback path. (See Fig. 4).

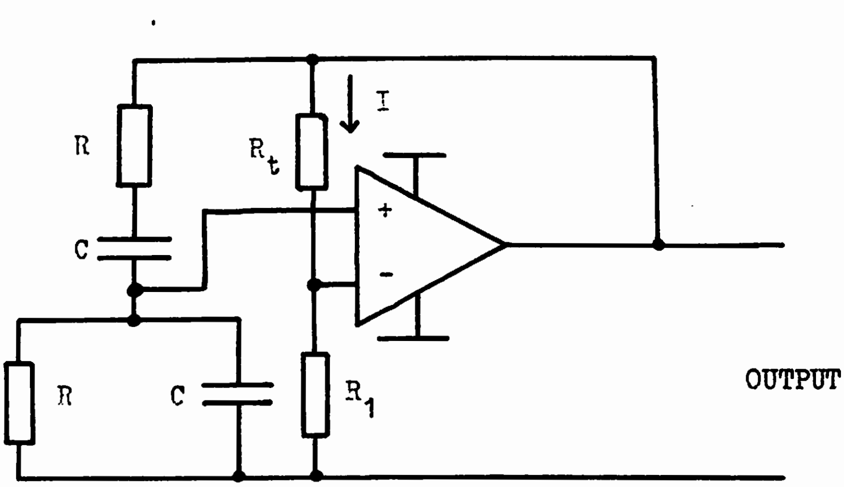


Fig. 4

Under normal operating conditions the amplifier gain with negative feedback is designed to be three.

i.e. $$\left(\frac{R_t + R_1}{R_1}\right) = 3$$

If R_t is a thermistor, its resistance will fall as the output level (and hence I) increases. This reduces the loop gain, and therefore stabilizes the output level.

5. Varying the Frequency

The frequency may be varied by changing the resistors or the capacitors. If variable resistors are used the capacitors can be switched to provide different ranges. Variable resistors suffer from track wear which can cause errors in the oscillator frequency, but they are often more convenient than variable capacitors.

Variable capacitors are more reliable and the tracking of ganged capacitors is easier to adjust. However, the largest value possible is approximately 1000 pF. At low frequencies, therefore, very high value resistors are required necessitating high input impedance amplifiers. Most B.B.C. designed AF oscillators (e.g. TS10 and EP14/1) use variable capacitor tuning with switched resistors for range changing.

With both systems it is difficult to obtain more than a 10:1 frquency range. If awider range is attempted then the frequency accuracy is impaired. The frequency range is the same as the range of the variable component since :

$$f = \frac{1}{2\pi CR}$$

Poor tracking between the tuning components will cause the gain needed to maintain oscillation to vary if the frequency is altered. This is taken care of by the thermistor; but it can cause the output level to jump about as the oscillator is tuned.

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6. LC Oscillators

LC Oscillators are more suitable for the higher frequencies (e.g. HF and VHF) as RC networks would require resistor and capacitor values which are impractically small. One of the simplest types is the tuned collector oscillator (see Fig. 5).

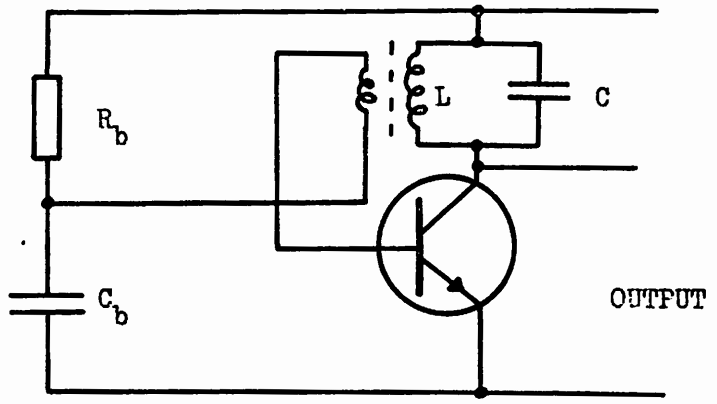

Fig. 5 Tuned Collector Oscillator

In this circuit the output is developed across the parallel resonant circuit, and a small proportion of it is fed back to the base of the transistor via the coupling winding. This circuit is designed to have a loop gain greater than unity in order to allow oscillations to start.

7. Automatic Bias

When the oscillations reach a certain amplitude, rectification of the feedback signal on positive half cycles by the forward biased base-emitter junction charges up C_b . The polarity is such that the bias voltage on the base is reduced. This reduces I_C causing gm to fall. The gain is thus reduced until an equilibrium condition is reached.

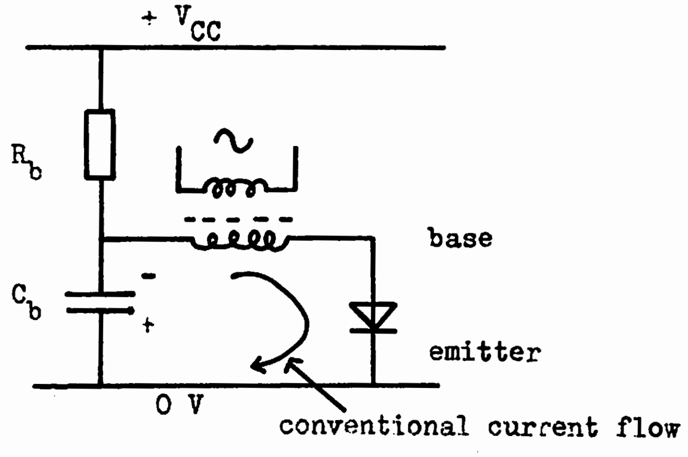

Fig. 6 Automatic Bias in an LC Oscilllator

If the loop gain is too high the transistor will be cut off every time the oscillations build up. This causes a "blocking action" where the oscillations occur in bursts, the rate of which is determined by the time constant of R_b and C_b (Squegging).

If Z_D is the dynamic impedance of the tuned circuit, then the Voltage Gain of the amplifier is given by $gm.Z_D$.

If N_1 = Number of turns on the primary
And N_2 = " " " " " secondary

Then, for unity loop gain,

$$\left[\frac{N_2}{N_1}\right] . gm.Z_D = 1$$

The number of coupling turns (N_2) required can thus be calculated for a given I_C.

The frequency of oscillation will be the same as the resonant frequency of the LC circuit :

$$f = \frac{1}{2\pi\sqrt{LC}}$$

If C is variable over a 10 : 1 range, then f will vary over a $\sqrt{10}$: 1 range.

Problem 3

An oscillator is built using the circuit of Fig. 5 . When oscillating normally, I_C = 1 mA . L = 1 mH , C = 100 nF. The loaded Q of the tuned circuit = 20. If L has 350 turns calculate how many turns are required on the coupling winding assuming all the flux in L links into the coupling winding ?

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8. Other LC Oscillators

In the tuned collector oscillator the necessary 180° phase shift in the feedback network was obtained using a transformer. An alternative is to use a tapped parallel tuned circuit :

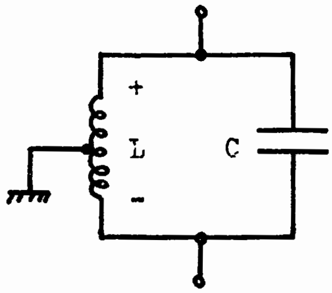
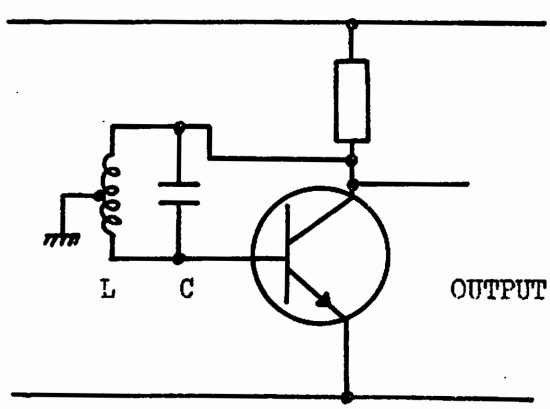


Fig. 7

Consider the circuit in Fig. 7 . If the tapping point is considered to be at zero RF potential then, at parallel resonance, the RF voltages developed at each end of the inductor will be in antiphase.

This network can be included between the base and collector of a transistor to give the Hartley oscillator. Other types of oscillator use similar techniques.

a) Hartley Oscillator



$$f = \frac{1}{2\pi\sqrt{LC}}$$

Fig. 8

The amount of feedback is determined by the position of the tapping point.

N.B. Base bias resistors and DC blocking capacitors have been omitted to aid clarity.

b) Colpitts Oscillator

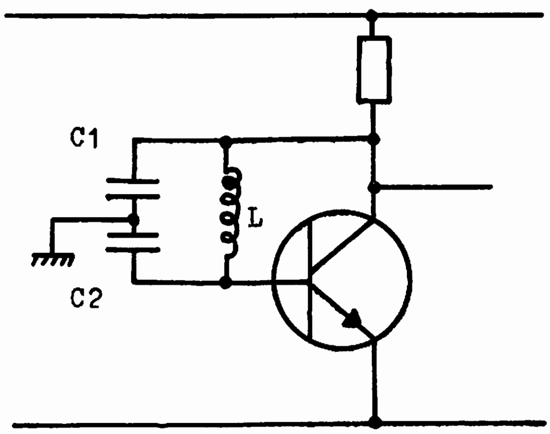


Fig. 9

In the Colpitts Oscillator the tap is in the capacitive branch. The circuit may be more familiar if it is redrawn with the collector at earth potential with respect to RF :

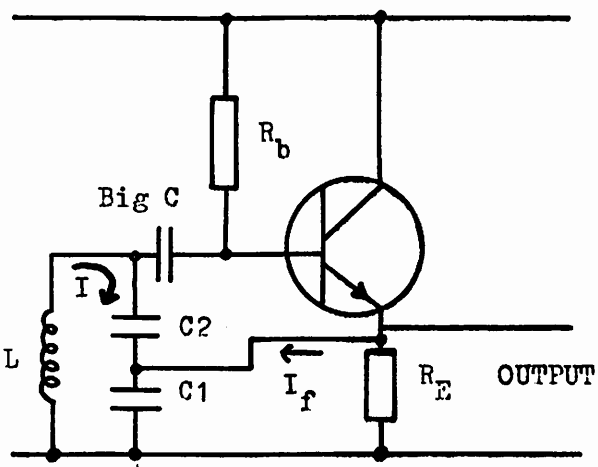


Fig. 10

Again the amount of feedback is determined by the tapping position.

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The feedback fraction β is given by $\frac{V_{fb}}{V_0}$

Where $V_{fb} = V_{be}$ (the AC voltage between base and emitter)

Thus $\beta = \frac{V_{C2}}{V_{C1}}$

Now , in a high Q parallel circuit at resonance, the circulating current (I) is much larger than the feedback current (I_f).

If we ignore I_f , then

$$\frac{V_{C2}}{V_{C1}} = \frac{X_{C2}}{X_{C1}}$$

Thus, $\beta = \frac{C1}{C2}$ .... (1)

The amplifier gain (A_o) is given by $gm.R_E$

Thus, for a pure sine wave output,

$$1 = \left(\frac{C1}{C2}\right) gm.R_E \qquad .... (2)$$

It is important to realise that the gm here is an average gm as the transistor is probably operating in either Class B or C . This means that the collector current is flowing in pulses causing gm to vary over the oscillation cycle . This limits the use of equation (2) as it is difficult to determine a meaningful value for gm.

However , the formula for β in equation (1) is more useful. For example, if a circuit is not oscillating due to lack of gain , or squegging due to excess gain , then the feedback fraction can be altered to cure the problem by varying the ratio of C1 to C2.

In many practical circuits the ratio $\left(\frac{C1}{C2}\right)$ may be close to unity.

c) Series Tuned Colpitts (Clapp)

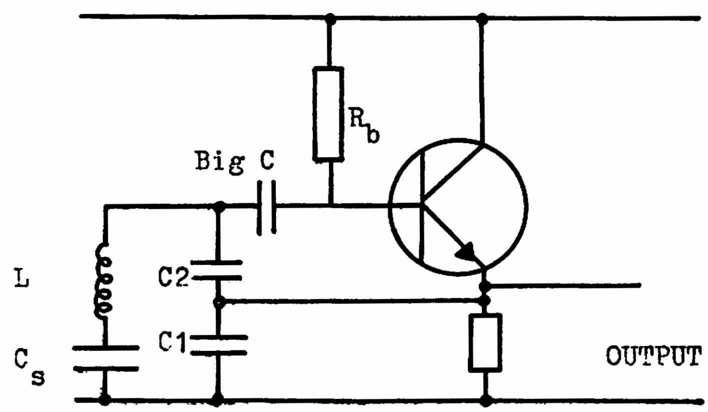


Fig. 11

The Colpitts circuit can be modified by including a capacitor (C_s) in series with the inductor. C_1 and C_2 are made much larger in value than C_s so that the resonant frequency is approximately given by :

$$f = \frac{1}{2\pi\sqrt{LC_s}}$$

The Clapp is theoretically more stable than the Colpitts as C_1 and C_2 effectively swamp any stray capacitances appearing across the transistor.

9. Frequency Stability

The frequency stability and accuracy of an oscillator depends mainly on two factors :

a) The temperature stability of the components.

b) The Q of the resonant circuit.

The dependence on temperature is fairly obvious - if the capacitances change with temperature then the resonant frequency will also change.

The dependence on Q is due to the slope of the phase/frequency characteristics. With high Q circuits, the phase changes more rapidly as the frequency goes through the resonant point than with low Q circuits. Any slight phase errors in the amplifier will then have less effect. (see Fig. 12)

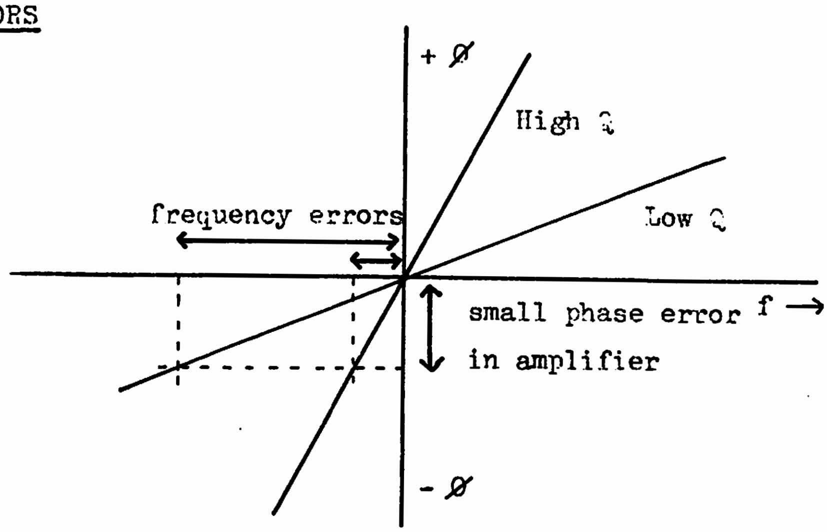
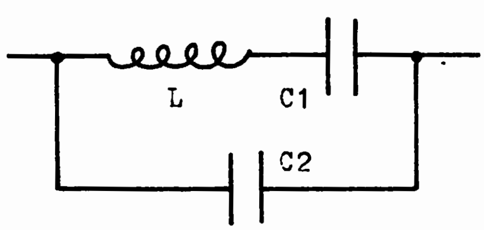


Fig. 12

Phase-Frequency characteristics near resonance for high and low Q circuits

10. Crystal Oscillators

Quartz crystals can be used where accurate single frequency oscillators are required. These have Q's of the order of 2000 to 5000. Their stability can be further improved by maintaining them at a constant temperature inside a crystal oven (usually at 60°C).



Typically : L = 1 H
C1 = 5 pF
C2 = 100 pF

Fig. 13 Equivalent circuit of a Quartz Crystal

The equivalent circuit of a quartz crystal is shown in Fig. 13. Because the effective L/C_1 ratio is high the Q is also very high.

The crystal has two resonant frequencies :

series resonant (f_s) and parallel resonant (f_p).

(f_s is always less than f_p by a few hundred Hz.)

Crystals can be used in a variety of different oscillator circuits, two of the most common are the Clapp and the Emitter-Coupled oscillators.

Typical Crystal Oscillator (Series Resonant Clapp)

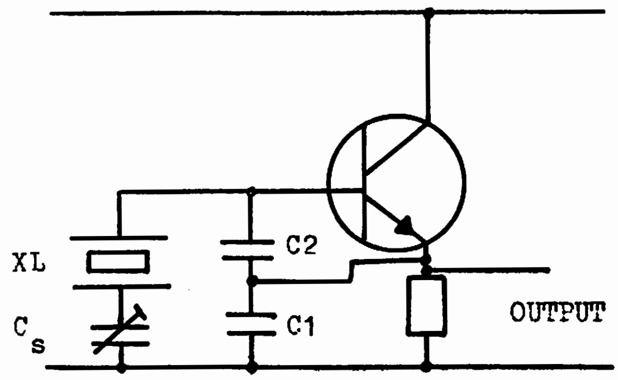


Fig. 14

C_s can be included in order to "trim" the crystal to the correct frequency (e.g. for a 1 MHz crystal the frequency variation $\approx$ 500 Hz)

Emitter - Coupled Oscillator

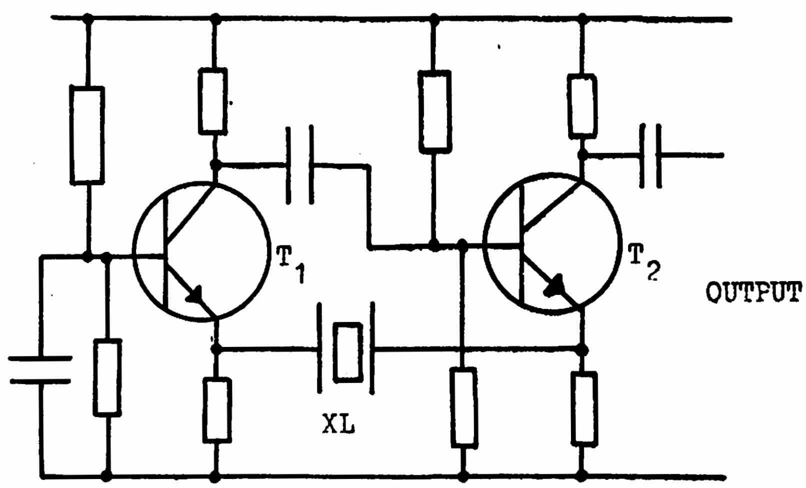


Fig. 15

This type of circuit is frequently found in BBC designed equipment. T_1 operates as a common base amplifier and T_2 operates as an emitter follower. The crystal (XL) feeds back some of the output signal from the emitter of T_2 to the emitter of T_1. The oscillation frequency is close to the series resonance of XL.

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ANSWERS TO PROBLEMS

Q.1 $f = 159$ Hz

Q.2 $C = 2.12$ nF

Q.3 $f = \dfrac{1}{2\pi\sqrt{LC}}$

$= 15.9$ kHz

$X_L = \omega L$

$= 100$

$Q = \dfrac{\omega L}{R}$

$R = \dfrac{100}{20}$

$= 5$

$Z_D = \dfrac{L}{CR}$

$= 2k$

$gm = 35\ I_C$

$= 35$ mA/V

Gain $= gm.\ Z_D$

$= 70$

Thus , the turns ratio must equal $\dfrac{1}{70}$

If the primary turns $= 350$

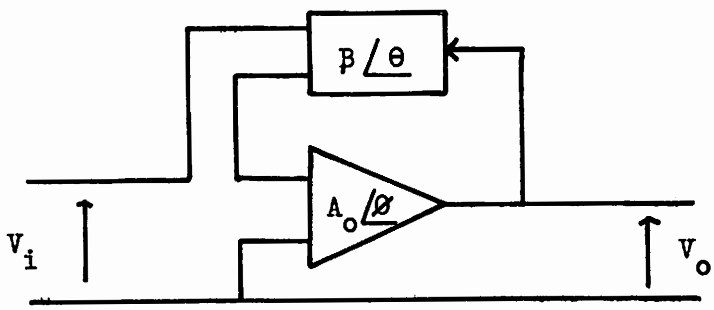
Then the secondary turns $= \dfrac{350}{70}$

$= 5$ Turns

APPENDIX

The Nyquist Criterion

Consider the following feedback system :



$$(V_i + \beta V_o) A_o = V_o$$

Thus $$V_i \cdot A_o = V_o - \beta V_o \cdot A_o$$

But $$A_v = \frac{V_o}{V_i}$$

So $$\boxed{A_v = \frac{A_o}{(1 - \beta A_o)}}$$

This is the gain of any amplifier with feedback where

A_o = gain without feedback

β = fraction of V_o fedback to the input.

For negative feedback βA_o must be maintained negative. If this condition is assumed to exist then the formula becomes :

$$A_v = \frac{A_o}{(1 + \beta A_o)} \qquad \text{(see NFB lectures)}$$

In this case the denominator is always > 1

Now, both β and A_o can be complex quantities (they can have a phase angle which does not equal 0^o)

i.e. $$\beta = \beta \angle \theta$$

And $$A_o = A_o \angle \emptyset$$

In the case of positive feedback it is possible to arrive at the condition :

$$(1 - \beta A_o) = 0 \qquad (\text{i.e. } \beta A_o = +1)$$

Giving $$A_v = \infty$$

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This is called the Barkhausen or Nyquist criterion and implies that the amplifier produces an output with no input (the condition for oscillation). A sine wave oscillator is designed so that this condition is satisfied only at one frequency.

Stability

The variation of both the magnitude and phase of βA_0 (the loop gain) with frequency is of considerable importance in determining the stability of a system.

βA_0 is , in general, a complex quantity as it contains both phase and magnitude information. In a Nyquist plot the Real part of βA_0 is plotted against the Imaginary part at different frequencies.

For example consider the amplifier circuit below with a simple CR feedback network :

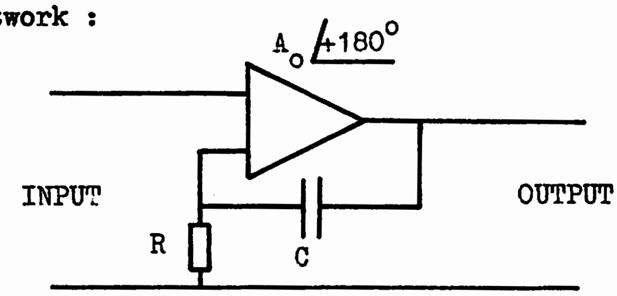
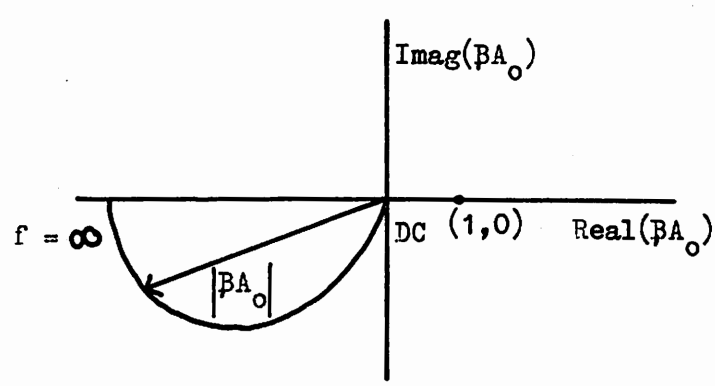


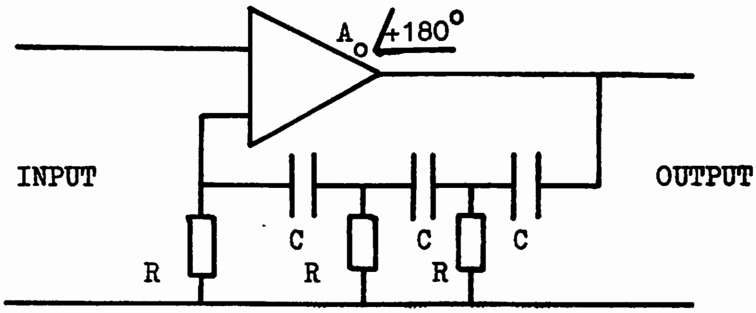
Fig. 16

If we assume that the gain A_0 is independent of the frequency we will obtain the following Nyquist Plot :

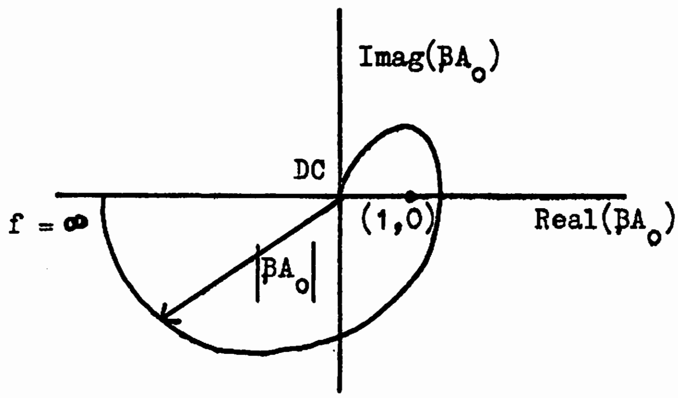


Now the Nyquist criterion states that provided the plot does not enclose the point (1,0) (i.e. $\beta A_0 = +1$) then the system will remain stable. This is true for the circuit in Fig. 16.

However, consider the same amplifier with three series CR networks in the feedback loop :



The Nyquist Plot for this circuit is shown below :



As you can see, this plot can enclose the point (1,0) if A_o is greater than a certain figure. This circuit is the basis of the phase shift oscillator.

R.W. Penman/RWP
10th March 1981