

Op-Amp Practical Applications: Design, Simulation and Implementation
Prof. Hardik Jeetendra Pandya
Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore

Lecture – 03
Introduction/ Summary on Op-amps Contd

Welcome to this module. And, this is in continuation with our last module. So, the idea here is that we are looking at the summary of integrated circuits, MOSFETs, op-amps and their applications. The reason of revising this particular slide is that we can use the knowledge that we acquire either in the last course or in the present modules for practical applications of op-amp.

So, to understand the op-amps, we need to understand the theory for op-amp, right. And that is why we are looking at the characteristics in the parameters of the op-amp. So, in the last module what we have discussed, we are discuss oscillators right. And in oscillators we have seen that there are several kind of oscillators depending on the waveforms, depending on the frequency, depending on the components used, depending on the feedback. And then we have also seen the Barkhausen criteria, right where we required the mode of a into beta it is again into feedback factor should be greater than equal to 1. And actually not or its and the phase shift that is the output signal that is feedback to the input the phase of that output signal that is feedback to the input should match the input signal phase right. That means, that feedback phase should be 0 or 360 degree.

Then after that we have seen RC oscillators, right. So, and in RC oscillators we have seen RC phase shift oscillator, how we can phase shift 180 degree signal from the output of the inverting amplifier using RC network. And then we have also seen Wien bridge oscillator where there is no need of a phase shift and that RLC which as the frequency sensitive arms by changing the value of RLC; we can change the frequency right.

So, we have also discussed that I if I go and use LLC instead of RLC. That means, inductor and capacitor than the oscillators can be used for high frequency applications, right. So, what are high frequency applications and how we can design LC oscillator?

So, let us see today how we can design LC oscillators.

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LC Oscillators

- The oscillators which use the elements L and C to produce oscillations are called LC Oscillators
- The circuit using L and C is called tank circuit or oscillatory circuit, which is an important part of LC oscillators. This circuit is also referred to as resonating circuit or tuned circuit.
- These oscillators are used for high frequency range from 200kHz up to few GHz. Due to high frequency range, these oscillators are often used for sources of RF energy
- LC tank circuit consists of elements L and C connected in parallel as shown in figure. Let the capacitor be initially charged from a DC source with polarities as shown in figure

Source: Electronic Devices and Circuits II by A.P. Godse et al

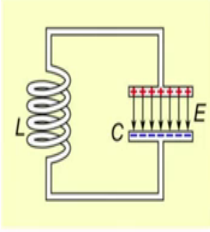
So, if you see on this screen what you see; that the oscillators which use the elements L and C to produce oscillations are called LC oscillators. The circuit using L and C is called tank circuit or oscillatory circuit which is an important part of LC oscillator circuit, this circuit is also referred to as resonating or tuned circuit, right. So, you can see on the left side L inductor and capacitor, this is the circuit used for oscillation in the LC oscillators. These oscillators are used for high frequency range like we discussed from 200 kilo hertz up to few gigahertz.

Now, since the frequency range is high this oscillators are also referred to as RF or sources for RF energy; resources of RF energy. LC tank oscillator circuit consists of L and C connected in parallel as shown in the figure. Let the capacitor be initially charged from a DC source with polarity as shown in the figure. So, suppose the DC source is there. And we are charging the capacitor in the polarity shown in figure what will happen, right.

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Operation of LC tank Circuit

- When the capacitor gets charged, the energy gets stored in the capacitor as electrostatic energy
- When such a charged capacitor is connected across inductor L in a tank circuit, the capacitor starts discharging through L as shown. The arrow indicates direction of flow of conventional current
- Due to such current flow, the magnetic field gets set up around the inductor L. Thus inductor starts storing the energy
- When the capacitor is fully discharged, maximum current flows through the circuit
- At this instant all the electrostatic energy gets stored as magnetic energy in the inductor L. This is shown in the Figure below



Source: Wikipedia.org

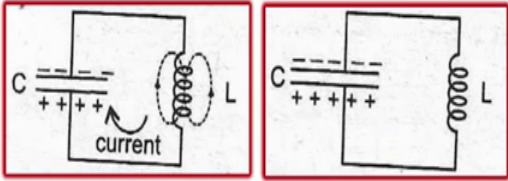
When the capacitor discharges; when the capacitor discharges; the energy that is stored in this capacitor right. When the capacitor charges, let us say first when it charges what happens. When it charges energy stored in the capacitor is electrostatic energy right. And when such a charged capacitor is connected across the inductor then what will happen the capacitor will start discharging. So, when it starts discharging through L right the magnetic field said gets set up around the inductor and thus inductance starts during the energy, right.

So, when capacitor is fully discharge maximum current flows through the circuit at this instant all electrostatic energy is converted to magnetic energy or is stored as a magnetic energy in the inductor.

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Operation of LC tank Circuit

- Now the magnetic field around L starts collapsing. As per Lenz's Law, this starts charging the capacitor with opposite polarity making lower plate positive and upper plate negative as shown



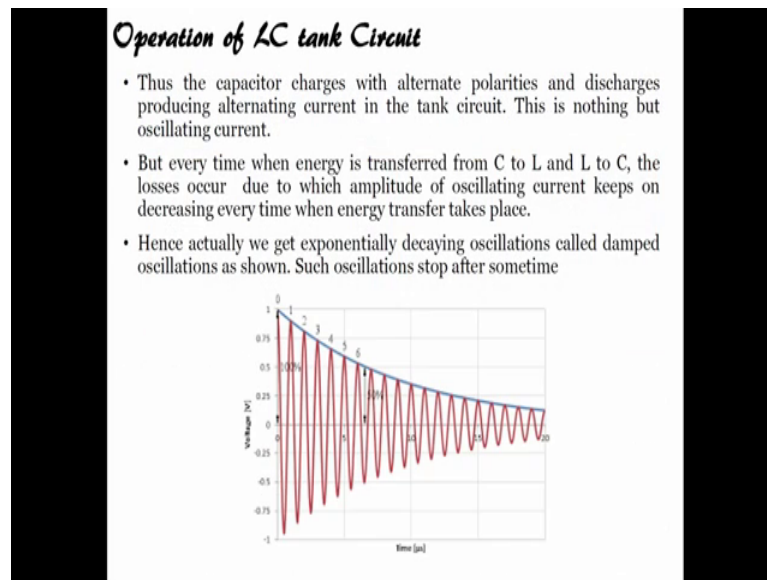
Source: Electronic Devices and Circuits II by A.P. Godse et al

- After some time, capacitor gets fully charged with opposite polarities, as compared to its initial polarities. The entire magnetic energy gets converted back to electrostatic energy in capacitor.
- Now the capacitor again starts discharging through inductor L. But the direction of current through the circuit is now opposite to the direction of current earlier in the circuit. Again electrostatic energy is converted to magnetic energy. When the capacitor is fully discharged, the magnetic field starts collapsing, charging the capacitor again in opposite direction

Now, when the magnetic field around L starts collapsing what will happen as per Lenz's law this starts charging the capacitor with the opposite polarity right. So, now, when discharge this starts collapsing the capacitor will start charging in the opposite polarity right making lower plate more positive and upper plate negative right. Now again after sometime when capacitor fully gets charged, it will start discharging and with the opposite polarities as compared to its initial polarities, right. Initially it was plus on the top plate minus on the bottom plate. Now it is plus on the bottom plate minus on the top plate.

So, now it is discharging with the opposite polarity compared to its initial polarity and the entire magnetic energy gets converted to electrostatic energy in capacitor wow that is earlier, we have seen. And now the electrostatic energy when it starts discharging is converted to magnetic energy once again, right. So, it is from when inductor discharge it is electrostatic energy that is stored in a capacitor when the capacitor discharges in the magnetic energy that is stored in the inductor, right. And this keeps on it is keeps on continuation until end and because of this; what will happen?

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What will happen that every time when this transfer of energy occurs, right, there is a loss and this loss causes the amplitude of the oscillating current decreasing?

See this loss because of the inductor charging and capacitor charging and capacitor charging and inductor discharging. And again this goes on continuation what happens every time this discharge and charging happened there is a loss in the circuit; And this results in the lower oscillation; oscillations gets down as you can see here and current keeps on decreasing, right. So, actually we get an exponential decay as you can see from the figure oscillations. And these are called damped oscillations this are called the damped oscillations, right. So, such oscillations stop after sometime of course, right.

So, initially you can see and then it is after sometime you can see that these oscillations are on the on the edge of die right; on the edge of die.

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Operation of LC tank Circuit

- In LC oscillator the transistor amplifier supplies this loss of energy at the proper times. The care of the proper polarity is taken by the feedback network.
- Thus LC tank circuit along with transistor amplifier can be used to obtain oscillators called LC oscillators. Due to supply of energy which is lost, the oscillations gets maintained hence called sustained oscillations or undamped oscillations.
- The frequency of oscillations generated by LC tank circuit depends on the values L and C and is given by

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

where L is in henry and C is in Farad

- Depending upon the type of tank circuit used, the LC oscillators are classified as ,

- 1.Colpitt's Oscillator
- 2.Hartley Oscillator

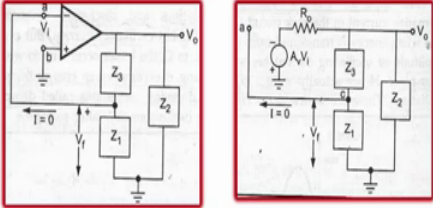
So, what will be what we can do right what we can do. So, in LC oscillators the transistor amplifier supplies this loss of energy at proper time. So, if I have a transistor amplifier then that will be energy that is loss during the charging and discharging of the inductor and capacitor right can be compensated using the transistor amplifier right. The LC circuit along with the transistor amplifier can be used to obtain oscillators called LC oscillators due to supply of energy which is lost the oscillation gets maintain; and hence called sustained oscillation or undamped oscillation.

Here the frequency of oscillation generated by LC is given by f equals to 1 by 2 pi root LC right. Where, L is in Henry and C is in Farad depending on the type of tank circuit the LC oscillators are classified into two categories: one is called Colpitt's oscillators, another one is called Hartley oscillator.

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Basic Form of LC Oscillator Circuit

- In this, the LC tuned circuit forms the feedback network while an op-amp, FET or BJT can be the active device in the amplifier stage
- The figure shows the basic form of LC Oscillator circuit with the gain of the amplifier as A_v . The amplifier output feeds the network consisting of impedances Z_1, Z_2, Z_3
- We will assume an active device with infinite input impedance such as a FET or op-amp. Then the basic circuit can be replaced by its linear equivalent circuit as shown in the Figure



- Amplifier provides a phase shift of 180° , while the feedback network provides an additional phase shift of 180° , to satisfy the required condition

Source: Electronic Devices and Circuits II by A.P. Godse et al

Now, LC or circuit forms the feedback network while an op-amp or FET or BJT can be active device the figure shows here. You can see the left side of the figure shows form of LC oscillator with gain of amplifier A , right amplifier output feeds the network consisting of impedances Z_1, Z_2, Z_3 .

We will assume that active device with infinite impedance such as a FET right or op-amp then the basic circuit can be replaced by linear equivalent circuits. So, if I want to replace this by linear equivalent circuit, I can draw like this right see its input impedance is infinite right and amplifier provides a phase shift of 180 degree, because it is the inverting terminal. We are applying the signal while the feedback network provides the phase shift of 180 degree. So, here the feedback network that we are we are designing or will be using it will provide another phase shift of 180 degree to satisfy the required oscillation, there is a that total phase shift should be 360 degree.

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Basic Form of LC Oscillator Circuit - Analysis

Analysis of Amplifier stage

- As input impedance of the amplifier is infinite, there is no current flowing towards the input terminals. Let R_o be the output impedance of the amplifier stage
- As $I = 0$, Z_1, Z_3 , appear in series and the combination in parallel with Z_2 . This equivalent is Z_L , the load impedance. The reduced circuit is as shown

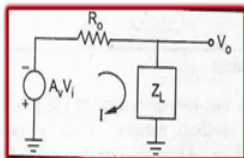
Therefore,

$$I = -\frac{A_v V_i}{R_o + Z_L}$$

And, $V_o = I Z_L$
 From these two equations, Gain of amplifier is,

$$A = \frac{V_o}{V_i} = -\frac{A_v Z_L}{R_o + Z_L}$$

Where A is the gain of the amplifier stage



Source: Electronic Devices and Circuits II by A.P. Godse et al

So, if you analyze this amplifier stage if analyze this amplifier stage what we get what we get is that I equals to minus A v V i upon R o Z L R o plus Z L, you can see from here right. And using the equation right what we can get gain of the amplifier V o by V i equal S to A v Z L upon R o plus Z L where a is the gain of the amplifier stage right.

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Basic Form of LC Oscillator Circuit - Analysis

Analysis of Feedback Stage

- For the feedback factor (β) calculation, consider the feedback circuit shown
- From the voltage division in parallel circuit we can write

$$\frac{V_f}{V_o} = \frac{Z_1}{Z_1 + Z_3}$$

But $\frac{V_f}{V_o} = \beta$, the feedback factor

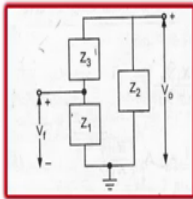
But as the phase shift of the feedback network is 180° ,

$$\beta = \frac{V_f}{V_o} = -\frac{Z_1}{Z_1 + Z_3}$$

And,

$$A\beta = \frac{A_v Z_L Z_1}{(R_o + Z_L)(Z_1 + Z_3)}$$

This is the required loop gain. Z_L can be written as $(Z_1 + Z_3) || Z_2$



Source: Electronic Devices and Circuits II by A.P. Godse et al

So, further when we analyze what we get we get beta equals to V i by V o and that will be nothing, but the Z 1 upon Z 1 plus Z 3 in terms of minus that is 180 degree phase shift. So, a beta would be this one.

So, this is the required loop gain this is the required loop gain Z_L can be written as Z_1 one plus Z_3 parallel to Z_2 , you can see here, right.

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Basic Form of LC Oscillator Circuit - Analysis

Analysis of Feedback Stage Contd..

- After substituting for the Z_1 value and further simplification we get $A\beta$ as

$$A\beta = \frac{A_v Z_1 Z_2}{R_0(Z_1 + Z_2 + Z_3) + Z_2(Z_1 + Z_3)}$$

As $Z_1, Z_2,$ and Z_3 are pure reactive elements
 $Z_1 = jX_1, Z_2 = jX_2, Z_3 = jX_3$

Where $X = L\omega$ (for an inductive reactance) and
 $X = -1/C\omega$ (for a capacitive reactance)

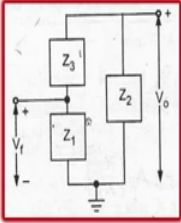
To have 180° phase shift, the imaginary part of denominator must be zero

$$X_1 + X_2 + X_3 = 0$$

And,

$$A\beta = \frac{A_v X_1 X_2}{X_2(X_1 + X_3)}$$

But, $X_1 + X_3 = -X_2$, therefore, $-A\beta = \frac{A_v X_1}{X_2}$



Source: Electronic Devices and Circuits II by A.P. Godse et al

So, if you substitute what we get you substitute. Then finally, when we when you solve this equation when you solve this equation what you get you get is that you are a beta right will be $A_v X_1$ by X_2 ; $A_v X_1$ by X_2 .

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Basic Form of LC Oscillator Circuit - Analysis

According to Barkhausen criterion, $-A\beta$ must be positive and must be greater than or equal to unity. As A_v is positive, the $-A\beta$ will be positive only when X_1 and X_2 will have same sign. This indicates that X_1 and X_2 must be of same type of reactances either both inductive or capacitive. While from the equation we can say that $X_3 = -(X_1 + X_2)$ must be inductive if X_1, X_2 are capacitive while X_3 must be capacitive if X_1, X_2 are inductive.

Table shows the various types of LC Oscillators depending on the design of the reactances X_1, X_2 and X_3

Oscillator Type	Reactance Elements in the Tank Circuit		
	X_1	X_2	X_3
Hartley Oscillator	L	L	C
Colpitts Oscillator	C	C	L

And A_v must be positive right here what we see is minus a into beta minus a into beta in the last line, we see that when we derive this when we solve this we get minus $A\beta$

equals to $A_v X_1$ by X_2 , but it cannot be minus right it should be X minus A_v should be positive and it must be greater than or equal to unity right we have seen that it is Barkhausen criterion.

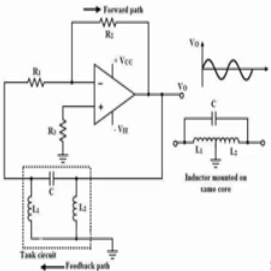
So, as a_v is positive minus a beta will be positive only when only when X_1 and X_2 will have same sign right when if X_1 and X_2 have same sign. Then only minus a beta can be positive right this indicates that X_1 and X_2 should be of same type of reactances you see here again minus a beta equals to a_v into X_1 by X_2 , but minus a beta should always be greater than equal to 1. That means, X_1 and X_2 should be same reactances right should be have same type of reactance. So, either we can use X_1 and X_2 as inductive or we can use X_2 and X_2 , X_1 and X_2 as capacitive, right either X_1 and X_2 as inductive or capacitive while we can also say that X_3 equals to minus X_1 . That means, that if X_1 and X_2 are capacitive X_3 should be inductive and if X_1 and X_2 are inductive X_2 should be X_3 should be capacitive, right. So either X_1 , and X_2 are inductive, then X_3 its capacitive X_3 if X_1 X_2 are capacitive, then X_3 should be inductive like vice versa.

So, if X_1 and X_2 are inductive and X_3 is capacitive, it is Hartley oscillator and if X_1 and X_2 are capacitive and X_3 is inductive and it is Colpitt's oscillator right, we have seen this.

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Hartley Oscillator using Op-amps

- The Hartley oscillator is one of the classical LC feedback circuits and used to generate high frequency waveforms or signals
- These can be implemented by using different circuit configurations. The major parts of the Hartley oscillators are the amplifier section and the tank section
- The tank section consists of two inductors and one capacitor
- Each section produces a phase shift of 180° of the AC signal voltage and hence it produces a sine wave voltage.



Source: www.electronicshub.org

Now, if I want to design Hartley oscillator, if I want to design Hartley oscillator, then this is the way to design Hartley oscillator. This is the tank circuit as we know right and this

can be implemented by using two inductors and one capacitor each section produces a phase shift of 180 degree, right each section produces 180 degree. And hence, it produces a sin voltage right produces a sin wave voltage.

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Hartley Oscillator using Op-amps-Operation

- The sine wave generated by the feedback circuit is coupled with the op-amp section. Then this wave is stabilized and inverted by the amplifier.
- The frequency of the oscillator is varied by using variable capacitor in the tank circuit keeping the feedback ratio and amplitude of the output constant for over a frequency range

$$F_o = \frac{1}{2\pi\sqrt{L_{eq}C}}$$

Where $L_{eq} = L_1 + L_2 + 2M$ or $L_1 + L_2$

- To generate the oscillation from this circuit, the amplifier gain must be selected greater than or at least equal to the ratio of two inductances. i.e

$$A_V = \frac{L_1}{L_2}$$

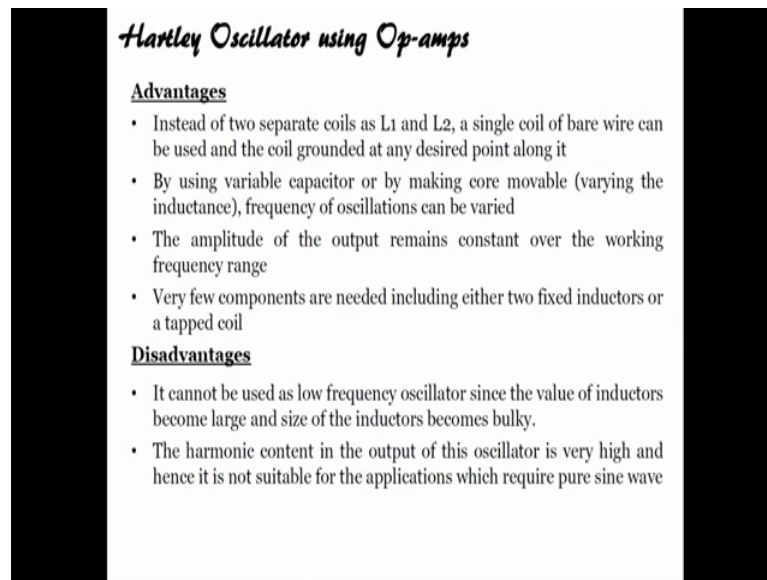
- If the mutual inductance exists between L_1 and L_2 because of the common core for these two coils, then the gain becomes

$$A_V = \frac{L_1 + M}{L_2 + M}$$

Here we know that the F_o equals to one upon two pi under root of L_{eq} into C right, because there are inductors L_1 and L_2 . So, where is L_{eq} L_{eq} is nothing, but $L_1 + L_2 + 2M$ or $L_1 + L_2$ to generation oscillation from this circuit the amplifier must have be selected greater than or at least equal to the ratio of 2 inductances, right. That means the amplifier gain should be at least equal to L_1 by L_2 . So, it should be greater than or equal to it should be greater than or equal to the ratio of L_1 and L_2 if there is a mutual inductance if there is a mutual inductance that exist between L_1 and L_2 , right.

Because of the common core, then the gain becomes $L_1 + M$ by $L_2 + M$.

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Hartley Oscillator using Op-amps

Advantages

- Instead of two separate coils as L_1 and L_2 , a single coil of bare wire can be used and the coil grounded at any desired point along it
- By using variable capacitor or by making core movable (varying the inductance), frequency of oscillations can be varied
- The amplitude of the output remains constant over the working frequency range
- Very few components are needed including either two fixed inductors or a tapped coil

Disadvantages

- It cannot be used as low frequency oscillator since the value of inductors become large and size of the inductors becomes bulky.
- The harmonic content in the output of this oscillator is very high and hence it is not suitable for the applications which require pure sine wave

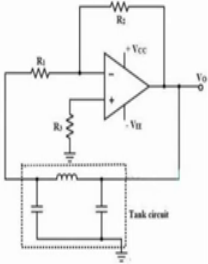
So, what is the advantage of this oscillator the advantage is that instead of two separate coils as L_1 and L_2 a single coil of a bare wire can be used. And the coil can be grounded at any desired point second is by using variable capacitor or by making core movable frequency of oscillations can be varied right. This, another advantage, amplitude of the output remains constant over the frequency range. and finally, very few components are required right for including either to fix inductors or tapped coil, but there are few limitations what are limitations it cannot be used for low frequency oscillation, right.

Since the value of inductors becomes large and size of the inductor becomes bulky right it is obvious correct the harmonic content in the output of this oscillator is very high. And hence it is not suitable for the application which requires pure sine wave, there is harmonic oscillations that limits its use for pure sine wave Colpitt's oscillator.

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Colpitts Oscillator

- An LC oscillator which uses two capacitive reactance and one inductive reactance in the feedback network i.e. tank circuit, it is called Colpitts Oscillator
- The op-amp provides the basic amplification needed while the feedback network is responsible for setting the oscillator frequency
- In the given circuit the op-amp is connected as an inverting amplifier with a high gain as compared with transistor circuit. The LC network is placed in a positive feedback of the operational amplifier
- When the power supply is given to the circuit, there is no signal, but the small noise voltages are amplified by the op-amp. This makes the both capacitor to starts charging and discharging
- The part of the signal across the capacitor C₂ is fed to the inverting amplifier. It is then amplified and keeps the network oscillating strongly



Source: www.electronicshub.org

Next is a Colpitt's oscillator, here we are using two capacitor and one inductor in this oscillator like we see here in the tank circuit there are two capacitors right and one inductor. So, here the op-amp provides the basic amplification needed with the feedback network in the given circuit op-amp is connected as inverting amplifier the high gain as compared with transistor circuit in the power supply given to the circuit, there is no signal, right. Initially there is no signal, but the small noise voltage are amplified with the help of amplifier op-amp amplifier.

This makes the both capacitors to charge and discharge write the part of signal across the capacitor C₂ is fed to the inverting amplifier right. Here, it is fed back to the inverting amplifier and then amplified and keeps the network oscillating strongly right. Initially through the noise voltage where amplifying the noise voltage with the help of amplifier with a feedback to the tank circuit and the part of signal is feedback to the amplifier and there is a strong oscillations which causes strong oscillations.

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Colpitts Oscillator

- The oscillating frequency of the Colpitts oscillator using op-amp is given by

$$F = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

Where $C_{eq} = \frac{C_1 C_2}{C_1 + C_2}$

Applications Of Colpitts Oscillator

- Colpitts oscillators are used for high frequency range and high frequency stability
- A surface acoustical wave (SAW) resonator
- Microwave applications
- Mobile and communication systems
- These are used in chaotic circuits which are capable to generate oscillations from audio frequency range to the optical band. These application areas include broadband communications, spectrum spreading, signal masking, etc.

Here we have same formula, but instead of L equivalent here we have c equivalent and we know that c equivalent is nothing but C_1, C_2 by $C_1 + C_2$; what are the applications of Colpitt's oscillator; Colpitt's oscillators are used for high frequency range and high frequency stability right, can also be used as a saw resonator a surface acoustical wave resonator used in microwave applications mobile and communication right. And these are used in chaotic circuits which are capable to generate oscillations from audio frequency to the optical band the application area include broadband communications spectrum spreading signal masking etcetera.

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Thank you

Arise! Awake! and stop not until the goal is reached. -Swami Vivekananda

Coming together is beginning, staying together is progress and working together is success. -Henry Ford

The key to success is action, and the essential in action is perseverance – Sun Yat-sen

So, this was the end of this particular summary of the oscillators, right. So, if you recall we have just understood right from the indicator circuit quickly right, then we went to op-amp its characteristics. Then we saw few amplifiers then we saw oscillators right and we also saw filters we also filters. Now in the in the next module, or in the next module or other in the next lecture we will see how we can implement design and implement circuits using operational amplifier. Like I said, slowly and gradually you will understand when you when you read from my earlier course till now, we are slowly and gradually increasing the tempo right we are increasing the tempo.

The reason is that we should start from basic right understand the concept grab it and then move on to applying it. So, you will see in this particular applications of op-amp it is little bit complicated than the earlier particles that we have seen in the last course right. And finally, we are actually designing signal conditioning device for measuring ECG as well as heart rate right and that is really complicated project.

So, let us see how we go further in the next lectures. I will see you in the next lecture, till then you just go through all the models right, keep your basic strong right refresh it, even you know it it is always good to refresh, right. I will see you in next class. Till then you take care. Bye.